UNIVERSITY OF THESSALY

# Optimized Video Transmission in Wireless Cooperative Networks

by

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MASTER THESIS

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# *Abstract*

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The objective of this master thesis is the optimization of cooperative video transmission in wireless fading channels and it consists of two parts.

In the first part, we propose a distortion optimized video streaming framework for maximizing the quality if the transmitted video in small-cell densely deployed cooperative wireless networks. To implement this idea without requiring new protocols to be deployed in the network elements, we work towards the full exploitation of the broadcast advantage that wireless networks offer. The broadcast channel is exploited first by allowing multiple relays, where each one is responsible for a small cell, to receive the transmissions of a source node without any requirements for additional message passing. Second, transmissions from the relays to their respective destination nodes can similarly be overheard by a neighboring small-cell relay. The combination of these two realistic assumptions for densely deployed small cells, allow us to apply the distortion-optimized streaming concept with simple algorithms. We propose lightweight video packet forwarding and overhearing algorithms that only process the packet headers and not the video content. Performance results demonstrate the efficacy of our scheme.

In the second part, we consider also an cooperative relay-based packetized video transmission in wireless networks. We propose algorithms for optimized relay selection that take into account in addition to the channel between the relays and the destination node and the content of each specific video packet. Our first algorithm that is designed for a narrowband channel and a system based on single-carrier modulation, selects jointly the optimal relay and video packet for forwarding. The key benefit of our approach is that it is fully distributed since it requires no explicit communication among the relays but it is only using information collected passively. Our first algorithm is also extended to a more advanced OFDM modulation scheme that is suitable for frequency selective channels. In this case in addition to optimized packet and relay selection we also jointly select the optimal power level for each subcarrier. We perform an extensive evaluation of our algorithms for different number of video flows and different number of available relays.

# ***ΠΕΡΙΛΗΨΗ ΣΤΑ ΕΛΛΗΝΙΚΑ***

Η παρούσα μεταπτυχιακή διατριβή έχει ως στόχο τη βελτιστοποίηση της ποιότητας του βίντεο που λαμβάνει ένας πελάτης, όταν αυτό μεταδίδεται σε ένα ασύρματο συνεργατικό δίκτυο και αποτελείται από δύο θεματικές ενότητες.

Στη πρώτη ενότητα, προτείνουμε μία 'distortion-optimized video streaming' τακτική για τη βελτιστοποίηση της ποιότητας του βίντεο που μεταδίδεται αν χρησιμοποιήσουμε μικρό-κυψέλες μικρής εμβέλειας ως ενδιάμεσους κόμβους σε ένα συνεργατικό ασύρματο δίκτυο. Για την υλοποίηση αυτής της ιδέας, χωρίς επιπλέον καινούργια πρωτόκολλα των στοιχειών του δικτύου να απαιτείται να υλοποιηθούν , εκμεταλλευτήκαμε τα πλεονεκτήματα που προσφέρει το 'broadcasting' στα ασύρματα δίκτυα. Το 'broadcast' κανάλι χρησιμοποιείται πρώτα επιτρέποντας πολλαπλούς ενδιάμεσους κόμβους (relays), κάθε ένας από τους οποίους έχει μία μικρό-κυψέλη, να λαμβάνουν τις μεταδόσεις της πηγής χωρίς την απαίτηση για επιπλέον επικοινωνία μέσω μηνυμάτων. Δεύτερον, οι μεταδόσεις από τους ενδιάμεσους κόμβους (relays) στους τελικούς αποδέκτες στους οποίους αντιστοιχούν μπορούν να 'ακουστούν' από τις γειτονικές μικρό-κυψέλες. Ο συνδυασμός των δύο παραπάνω υποθέσεων για μικρό- κυψέλες μικρής εμβέλειας, μας επιτρέπει να υιοθετήσουμε την 'distortion- optimized streaming' ιδέα με απλούς αλγορίθμους. Γι' αυτό προτείνουμε, μία απλή μετάδοση των πακέτων του βίντεο σε συνδυασμό με τον 'overhearing' αλγόριθμο, ο οποίος μεταδίδει μόνο τα 'packet headers' και όχι ολόκληρο το περιεχόμενο του βίντεο. Τα αποτελέσματα των προσομοιώσεων που υλοποιήθηκαν αποδεικνύουν την ευστάθεια του παραπάνω αλγορίθμου.

Στο δεύτερο μέρος, εξετάζουμε και πάλι τη μετάδοση πακεταρισμένου βίντεο σε ασύρματα συνεργατικά δίκτυα. Προτείνουμε μία βελτιστοποιημένη τακτική για 'relay selection', η οποία λαμβάνει υπόψη και το περιεχόμενο του κάθε πακέτου του βίντεο. Ο πρώτος αλγόριθμος μας, αφορά ένα 'narrowband' κανάλι με 'single- carrier' διαμόρφωση, επιλέγει όχι μόνο τον 'καλύτερο' ενδιάμεσο κόμβο(relay) αλλά και το βέλτιστο πακέτο του βίντεο για μετάδοση. Το κύριο πλεονέκτημα του αλγορίθμου μας είναι ότι είναι πλήρως κατανεμημένος, μιας και δεν απαιτεί καμία επικοινωνία μεταξύ των ενδιάμεσων κόμβων(relays), αφού αυτοί συλλέγουν πληροφορία μόνο 'παθητικά' από ότι μπορούν να 'ακούσουν' από τους γειτονικούς ενδιάμεσους κόμβους. Στη συνέχεια, ο παραπάνω αλγόριθμος μας εξελίχθηκε σε ένα πιο προχωρημένο σχήμα με 'OFDM' διαμόρφωση που είναι κατάλληλο και για την επιλογή της συχνότητας των καναλιών. Σε αυτή την περίπτωση, επιλέγουμε όχι μόνο τον 'καλύτερο' ενδιάμεσο κόμβο(relay) και το 'βέλτιστο' πακέτο του βίντεο, αλλά και το 'βέλτιστο' επίπεδο ενέργειας για κάθε 'subcarrier'. Τέλος, ελέγξαμε την ορθότητα των παραπάνω αλγορίθμων μέσα από ένα μεγάλο αριθμό προσομοιώσεων για διαφορετικό αριθμό από βίντεο και ενδιάμεσους κόμβους(relays).

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I would like to acknowledge the help and support of Dr. Antonios Argyriou who was the supervisor of this thesis. I would also like to acknowledge the support from Dr. Leandros Tassiulas.

# Contents

*Dedicated to my family…*

# Chapter 1

# Introduction

Today's smartphones are equipped with significant processing, storage and sensing capabilities, as well as wireless connectivity through cellular, WiFi and Bluetooth. They provide ubiquitous Internet access, primarily through their cellular connection and secondarily through WiFi, and enable a plethora of new applications. Among these applications, video is increasingly popular. However, video communication over mobile broadband is challenging due to limitations in bandwidth and difficulties in maintaining high reliability, quality, and latency demands imposed by rich multimedia applications. In the meantime, mobile video traffic is growing at an immense rate due to significant consumer demand, with the projected share of video constituting more than two-thirds of total mobile traffic by 2015. So, the most significant problem of video communication over wireless is the well known reliability problem. Reliability problems originate in shadowing, path loss and fading. The above problems can significantly distort the quality of video. For example, the group of frames (GOP) of a video has the following frame-type pattern IBBBP ..., there are three B frames between every two P frames. If a I frame lost through fading, the following frames (B and P frames) will not decode. So the entire GOP will not display causing a significant distortion at receiving quality of video.

To address this massive demand for high quality video, mobile network operators have several options in their arsenal. One solution to the above demand is the use of multiple antennas in order to create diversity for the transmitted signals and lead eventually to higher throughput. But, with this adoption a lot of resources are consumed. The only alternative to the above solution is the diversity that offers the cooperation. More specifically, a group of relays are deployed at different locations within the coverage area of single cell. Relays can be deployed in small- cell configurations in order to process the received signal from the base station (BS) before forwarding it to the destination node.

In this master thesis, we studied different approaches for optimizing the quality of transmitted video at a wireless cooperative network. The target is, if a source node has one or more video flows to transmit each one of them ’unicast’ to a specific destination node with the optimum quality. At the second chapter, we present a rate- distortion optimization method(R-D) with an innovative ”packet- overhearing” tactic at relays. Then, at the third chapter, we present a ”video- aware” relay selection method in single carrier and OFDM wireless systems.With this ”video- aware” relay selection method were observed significant performance improvements for the total simulations that has be done.

# Chapter 2

# Optimizing Video Streaming in Dense Small-Cell Wireless Relay Networks with Packet Overhearing

## 2.1 Introduction

Video streaming in wireless networks is more relevant than ever due to the widespread adoption of mobile devices that are capable of handling sophisticated video decoding algorithms. One important characteristic of wireless mobile devices that is pertinent to video streaming is that the video sequences are consumed quickly and at a quality level that depends on the capabilities of the device. This means that in order to ensure optimal adaptation to the dynamic network conditions, user needs, and device specifications, media streaming servers can store video content that is tagged with information regarding its quality at the very fine level of individual packets [1].

However, allowing a server to adapt the rate of the transmitted video sequence in order to match the conditions of the communication channel, does not address the most important problem in wireless networks which is the well known reliability problem. Reliability problems originate in shadowing, path loss, and fading [2]. Thus, the only fundamental way to combat these effects without consuming more resources is through diversity [2]. With cooperative diversity relay node processes the received signal from the source/Base Station (BS) before forwarding to the destination. This type of cooperation among different network nodes provides a flexible alternative to the use of multiple antennas in order to create diversity for the transmitted signals. This cooperative communication paradigm, fits well with emerging small-cell networks where the envisioned network configuration includes several small cell base stations (SCBS) with overlapping coverage [3]. Thus, besides the single SCBS node that a destination may be associated to, neighboring SCBS may also be able to be used as relays (Fig. 2.1). The dense deployment of

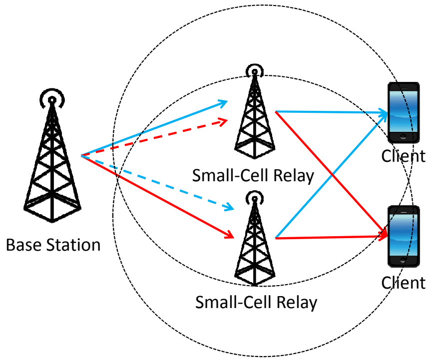


FIGURE 2.1: In the small-cell relay network topology adopted in this paper, each client receives a different video stream through an assigned relay. Solid lines indicate these transmissions. Other small-cell relays may also forward packets to a non-assigned client. Dashed lines indicate overhearing due to the dense small-cell deployment. The relays make the packet forwarding decisions in a distributed fashion by collecting information only through passive wireless packet overhearing.

these wireless networks allows the aforementioned type of cooperation that increase the achievable rates and decrease susceptibility to channel variations [4]. We believe that the functionality of these small-cell relays may be progressively enhanced with application-layer processing if substantial benefits to the user can be demonstrated.

Wireless cooperative transmission of video streams has been studied in the literature considerably the last few years but the term *cooperative transmission* may span techniques applicable at different layers of the protocol stack. The case of layered encoded video in conjunction with the novel physical layer (PHY) technique of distributed space-time coding (DSTC) was studied in [5]. DSTC was employed in that work in order to improve the decoding of the PHY symbols when multiple receivers are involved. Nevertheless, distortion-optimized techniques across the transmitted video sequences were not used. Besides the previously described work that employs cooperation at the PHY, packet-based cooperation has been more thoroughly investigated. Digital network coding (NC) is a modern technique for packet-level cooperation and it was also studied as a scheme for improving the quality of transmitted video. State-of-art wireless cooperative techniques at the network layer combine algebraic network coding and video transmission [6–9]. In these works the authors employ linear network codes for mixing video packets before transmission to a multicast group of clients. However, one assumption of wireless network coding is that the coded broadcasted packets must be acknowledged by all the participating relays in order to improve the selection of coded packets. Nodes must exchange out-of-band buffer maps for ensuring decodability of the selected code and this has to take place between the destination nodes and intermediate relays [6]. Furthermore, NC is suitable for multicast delivery for maximizing the throughput gains, but in the setup we adopt the projected gains are expected to be minimal. Due to the small-cell nature of the system configuration, the relays in Fig. 2.1 will be able to reach a small number of clients/destinations that are located in their neighborhood and are unlikely to desire the same video stream. Therefore, small-cell relays are not intended to help with the multicast traffic delivery to several nodes but are being deployed for the purpose of improving the performance of a single client/destination [3].

In this chapter we focus on a fundamental property of a wireless channel which is its broadcast nature and we try to exploit this property for further optimization of the video streaming process in densely deployed small-cell wireless relay networks. Our additional goal is to introduce the minimum possible modifications in network elements. Interestingly, by exploiting wireless broadcasting in a small-cell relay network classic utility optimization can be readily implemented in a distributed fashion without resorting to the also well-known primal-dual decomposition methods [10]. The new potential for optimization is only unlocked by careful coupling of the utility-optimized video streaming process and that of wireless broadcasting-based cooperation. The concrete contributions of this work are outlined below.

- We propose a framework for distortion-optimized streaming in a wireless relay network (topology in Fig. 2.1). We evaluate the impact of different numbers of relay nodes on a video streaming system that employs both the non-optimized and distortion-optimized approaches. We also define our framework so as to support multi-flow video transmission and in this case the rate is allocated across the different transmitting video streams.
- Our second contribution is on the actual enforcement of the calculated rate allocation that is implemented through packet forwarding/dropping. We propose a protocol that allows the relays to make decisions for packet forwarding/dropping on a hop-by-hop basis and in a completely distributed fashion. Our protocol ensures operation in the optimal point of the R-D curve of the transmitted video sequence by avoiding duplicate video packet forwarding from different relays. The last event will normally occur since many of the relays may have the same video packets. This is accomplished only by using overhearing of DATA and ACK packet transmissions that are employed in every wireless communication protocol, and without requiring any out-of-band signaling, exchange of buffer maps, or specialized message passing.

## 2.2 System Model and Assumptions

**Network Model:** We consider the unicast streaming of a set $S \triangleq \{1, 2, .., n, .., N\}$ of $N$ pre-compressed and packetized video streams from a single source node, the MBS, to $N$ destination nodes that each one is interested in a specific video stream. Besides the MBS and the destinations, the network also includes $M$ SCBS/relays that are not the consumers of the video streams but their task is to aid by forwarding traffic to the destinations as seen in Fig. 2.1. So in the adopted communication model the backhaul link from the MBS to the SCBS is also a wireless link [11].

The $M$ neighboring SCBSs due to their dense deployment (e.g. in Fig. 2.1 the destination that receives the ”blue” video flow can also receive packets from the SCBS that forwards the ”red” flow). Note here that it may be that $M > N$, e.g. if we try to transmit one video flow but there is one or more SCBS in the neighborhood that can help but they do not currently receive video. *To identify the number of $M$, i.e. how many relays can help a specific destination, the destination can overhear the periodic advertisements from neighboring SCBSs. Subsequently, it informs the MBS with this information regarding the neighborhood of a specific destination.*

**Video Source Rate Allocation and Packet Transmission:** The source transmits video flow $n$ at rate $r_n$ by allocating optimally the capacity of the relay channel. To accomplish that, the packet error rate $\rho$ is periodically collected at the source from all the destinations (i.e only the channel statistics are known), and then the source executes a rate allocation algorithm by using convex utility optimization, in order to derive the optimal $r_n^*$ for each flow. Since we perform rate allocation at the source based on information for the complete end-to-end channel, we know that all the packets that are transmitted from the source should reach the destination and not be dropped. Therefore, the relays know that they must transmit all the packets in a FIFO order.

**Channel Access:** Generally, resource allocation cellular wireless networks is exercised centrally by the radio resource manager (RRM). The RRM allocates not only time but also frequency and power resources [12]. The nodes inside the cell access the channel independently through a scheme that ensures orthogonal access. In particular here we assume the most general case of a fully distributed scheme like CSMA/CA. We do not delve further into how CSMA/CA works but we abstract/model the impact of specific resource allocation decisions in terms of the average rate that the specific group of nodes can achieve.

**Video Content Model:** The rate-distortion (R-D) information associated with packet $i$ is contained in each packet header and it consists of its size $\Delta R(i)$ in bytes, and the importance of the packet for the overall reconstruction quality of the media presentation denoted as $\Delta D(i)$ [1]. In practice, $\Delta D(i)$ is the total increase in the mean square error (MSE) distortion that will affect the video stream if the packet is not delivered to the client by its prescribed deadline.

**Channel Model and PHY Modulation:** All the channels are considered to be narrowband block-fading Rayleigh. The channel coefficients are quasi-stationary, that is they remain constant for the coherence time of the channel (slow fading). Additive white Gaussian noise (AWGN) with zero mean and unit variance is assumed at the SCBSs/relays and the destinations. At the PHY we assume the use of single-carrier (SC) PSK modulation. We also assume that each transmitter employs a type of ARQ (e.h. hybrid ARQ) that is typical is cellular standards. Also we only assume channel state information at the receiver (CSIR).

**Implementation Requirements:** Regarding the proposed system we have defined a set of strict requirements motivated by current wireless standards that make use of the relay-based architecture [13]. In our system we do not allow the involved nodes to exchange any type of out-of-band information for a video flow. Second, the clients/destinations should not be required to overhear packets so as to minimize power consumption. Third, we do not allow any type of operations on the data payload at the relays (e.g. application-layer coding) besides a decision regarding their forwarding or discarding. Thus, the relays do not collect information pertinent to the used algorithm by using a specialized protocol and message passing. We want the relays to passively overhear other transmissions and based only on this information to take local actions for each specific video packet. We believe that this is an important design choice since it can be readily and incrementally be deployed in existing networks. Finally, we do not consider that there is practical concerns for storing data from neighboring and overheard nodes since we consider our optimization horizon to be within a few GOPs. SCBSs, among other devices, can be equipped with fairly inexpensive magnetic or even solid state drives that may store multiple video files and not just a portion of it [14].

## 2.3 System Overview

Regarding the proposed framework it is comprised of two basic components: 1) rate allocation for the relay network, 2) an algorithm for video packet transmission, forwarding, and overhearing. First we provide an overview of these components and in the next three sections we analyze them at a finer level of detail.

The first task of the source node is to estimate the end-to-end throughput. The packet error rate information from all the destinations is periodically collected at the source (e.g. through RTP messages) in order perform this task. Next, the source performs the rate allocation step through utility optimization by considering the throughput estimate. It then transmits with broadcast mode the video packets that are the optimal according to this calculation. Each relay node receives an arbitrary group of packets. Because the channel is broadcast, many relays might receive the same packet. Thus, the next problem that our system must is solve is to ensure that each packet is forwarded only once from at least one relay and not from more. The solution is briefly explained as follows and it is instrumental in the development of the distortion-optimized streaming framework of this paper. When a relay obtains access to the channel, it transmits packets that are optimal. However, it also overhears the DATA/ACK transmissions of the remaining relays with the destination when they obtain access to channel, and it ensures that no duplicate packets are transmitted. In this way the data rate on the second hop is fully utilized by ensuring that each relay has a ”global” picture of the available data rate on the second hop and the transmitted packets from other nodes. *In other words the relays must know only which relay* *transmitted what but not who has what*. Finally, when the relay node ensures that a packet is optimal and has not been transmitted by any other node, it transmits it and waits for an ACK from the destination (unicast transmission).

## 2.4 Distortion-Optimized Rate Allocation

In this section we answer the question of how the source calculates the optimal streaming rate for a number of video streams destined to different destination nodes.

We formulate our optimization problem as a utility maximization. Different utility functions can be employed by the senders. In our case, the utility function is defined as the reduction of the reconstruction distortion of the media presentation, i.e.,

$$u(r) = \sum_i \Delta D(i) \quad \text{with} \quad \sum_i \Delta R(i) \leq r, \tag{2.1}$$

It is important to note at this point that the value of the MSE distortion in $\Delta D(i)$ includes both the distortion that is added when packet $i$ is lost and also the packets that have a decoding dependency with $i$[1]. In this way the utility formulation considers also the possible drift that might occur due to the loss of particular packets/video frames. Now, in order to compute the utility $u(r)$ in (2.1) we previously label the media packets comprising the presentation in terms of importance using the procedure from [15]. Therefore, the index $i$ in the summations in (2.1) enumerates the most important media packets in the presentation up to a data rate of $r$. In other words, $u(r)$ corresponds to the cumulative utility of the most important packets up to the rate point $r$.

However, the actual utility of the received packets must account for the lost media units. This should be done such that the overall utility $U_n(j)$ of the GOP $j$ that belongs to the media flow $n$ is maximized (We drop the GOP index next). According to the above, the overall utility for flow $n$ is defined as

$$U_n(r_n) = u[r_n(1 - \rho_n)], \tag{2.2}$$

where it is the utility of all the packets of GOP $j$ up to rate point $r_n(1 - \rho_n)$. This rate point corresponds to the packets that are not lost.

---

[1] For example the $\Delta D$ for an I frame includes the $\Delta D$ of the P and B frames that depend on it.

Using the notation introduced previously we can write the optimization problem as

$$\begin{aligned} & \max \sum_{n=1}^{N} U_n(r_n) \\ \text{s.t.} \quad & \sum_{n=1}^{N} r_n \leq T, \\ & r_n \geq 0, \ \ n = 1, ..., N \\ & U_n(r_n) \in \mathcal{U}_n, \ \ n = 1, ..., N \end{aligned} \tag{2.3}$$

The last constraint ensures that the utility value for each flow belongs to a valid RD point in the discrete set $\mathcal{U}_n$. We proceed here to solve the optimization problem in (2.3). For this problem, we can apply Lagrange duality [16] to the first constraint in (2.3) to produce the following partial Lagrangian

$$L_n(\lambda, \vec{r}) \ \ = \ \sum_{n=1}^{N} U_n(r_n) - \lambda \cdot (\sum_{n=1}^{N} r_n - T), \tag{2.4}$$

where $\lambda > 0$ is the Lagrange multiplier. Similarly, $r_n$ is current instantaneous rate allocation for flow $n$.

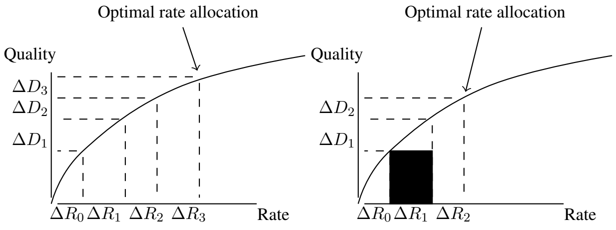
Now, (2.3) represents a concave optimization problem with linear constraints for the rate region. The Lagrange multiplier expresses the price of each selected rate allocation for flow $n$. It is known that if $\lambda^*$ is the optimal solution for the dual problem, then the corresponding $r^*(\lambda^*)$ is the solution to the primal problem defined in (2.3). It can be shown that the following two equations represent a solution for the primal-dual optimization problems [16]. First, the source computes the optimal rate allocation for flow $n$

$$r_n^* = \arg\max_{r_n} \Big\{ U_n(r_n) - \lambda r_n \Big\} \quad n = 1, ..., N. \tag{2.5}$$

Then, given $r_n^*$ we employ a sub-gradient method [17] to update the value of $\lambda$ as follows

$$\lambda(t+1) = \max \big\{ 0, \lambda(t) + \beta \Big( \sum_{n=1}^{N} r_n^* - T \Big) \big\}. \tag{2.6}$$

In the above equation $\beta$ is a small constant that is appropriately selected. Sub-gradient adaptation methods such as (2.6) are typically used in optimization problems involving Lagrange relaxation. Lastly, (2.5) and (2.6) are consecutively applied every time and node $n$ performs rate allocation on its outgoing link. Thus, the rate allocation algorithm presented in this section calculates the Lagrangian multiplier for the transmitted bitstream at each sender separately.



(a) Source (b) Relay

FIGURE 2.2: Representation of the R-D curve: (a) The range of optimal video packets can be easily identified and transmitted from the source. (b) At the relay the optimal R-D point may be different due to reduced bandwidth availability. Also the randomness of the wireless channel results in packet losses (dark-shaded block) that are arbitrarily located in the R-D curve. The proposed overhearing algorithm ensures that missing video packets from the correct operating points in the RD curve are forwarded from the relays.

## 2.5 Cooperative Video Packet Transmission, Forwarding, and Overhearing Algorithms

Until know we described how to estimate in theory the optimal transmission rate for a video stream given the underlying relay network. If the rate of the stream is higher than the available in the channel what can we do both at the source and especially at the relays? How can we select which relay will forward which specific packet that satisfies the distortion-optimal rate allocation?

### 2.5.1 Stream Adaptation at the Source

As we explained in Section 2.2, in the proposed system the destination periodically forward the average PER to the source for estimating the average throughput since the broadcast transmission lacks acknowledgments. With this information, the source estimates the aggregate throughput, executes the rate allocation for the first hop, and broadcasts the optimal packets according to the algorithms explained so far. Now, as shown in [15] the optimal rates $r_n^*$ can be efficiently enforced using the R-D characterization of the media packets comprising a flow. In particular, if $\Delta D(i_n)/\Delta R(i_n)$ is the utility gradient of packet $i_n$, i.e., packet $i$ from flow $n$, in order to achieve the optimal rate point the source node should transmit the video packets if $\Delta D(i_n)/\Delta R(i_n) > \lambda^*$ (Fig. 2.2(a)). Since our communication channel operates under an orthogonal channel access scheme, the calculated optimal rate allocations are mapped to different slots/frequencies.

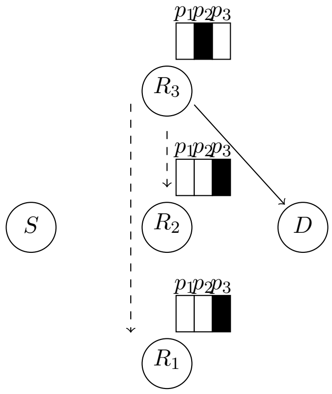


FIGURE 2.3: Example of the overhearing algorithm operation when three packets ($p_1, p_2, p_3$) have been transmitted. Dark-shaded blocks indicate packets that are not available at a particular relay because they were lost during transmission from the source.

### 2.5.2 Packet Overhearing Algorithm

For enforcing the optimal rate allocation at the relays a new algorithm is needed. At the core of the proposed framework is the overhearing of packet transmissions from the multiple small-cell relays. A pseudo-code for the overhearing algorithm is presented in the procedure $listen\_pkt(l)$ of Fig. 2.4. In our system the source and the relays employ a type of pseudo-broadcast by transmitting with unicast to their respective next hop and allowing overhearing. Fig. 2.3 depicts the contents of the receive buffers at each relay for an example with three small cell relays. Because of the randomness of the wireless channel different broadcasted packets from the source will be received at different relays. When a relay forwards a packet to the next hop destination, the remaining relay nodes also overhear this transmission and its acknowledgment. In this example the first transmitted and overheard packet is $p_1$. By following this approach, the neighboring relays know that in the case they also have the packet in their buffer, there is no need to transmit it in the next time slot that they obtain the channel. Instead, they may discard it (lines 10-11 in Fig. 2.4). In case a packet transmission fails this can be detected by the lack of an ACK and all the relays retain the lost packet since any one of them may transmit in in the next opportunity. Therefore, the overhearing algorithm allows the relays to forward uniquely each packet to the next hop.

## 2.6 Performance Evaluation

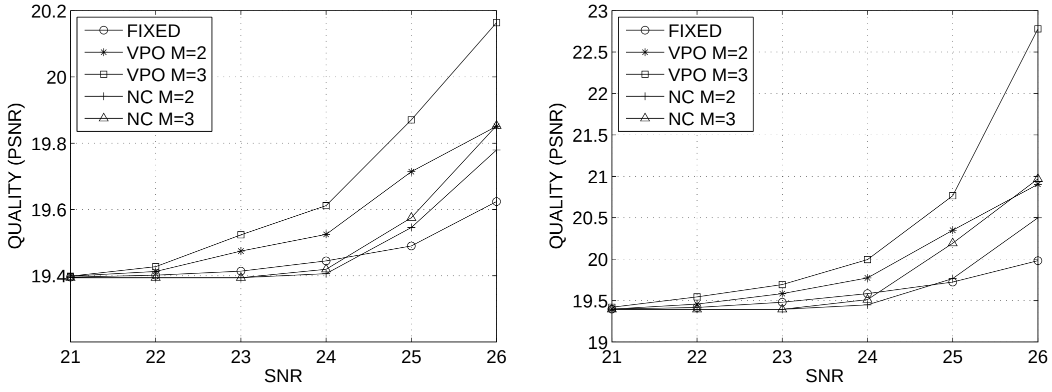
In this section, we present a comprehensive evaluation of the proposed algorithms comprising our framework through simulations. We have implemented both the PHY outlined earlier, the video streaming system, and the overhearing and forwarding algorithms in Matlab. The number of small-cell relay nodes $M$ is kept small since the simulator operates at the PHY symbol level

```
$transmit\_pkt(l)$
if if $l$ not in $ovhr\_buffer$ then
    if if $l \rightarrow \lambda \geq \lambda^*$ then
        $tx\_pkt\_phy(l)$
    else
        Drop $l$
    end if
else
    Drop $l$
end if
$listen\_pkt(l)$
if $l$ ==DATA then
    if $l \rightarrow src$ ==source then
        $add(src\_buffer)$
    end if
    if $l \rightarrow dst$ ==destination then
        $add(ovhr\_buffer)$
    end if
else if $l$ ==ACK then
    if $l \rightarrow src$ ==destination then
        $remove(l, src\_buffer)$
        $remove(l, ovhr\_buffer)$
    end if
end if
```

FIGURE 2.4: Pseudo-code for the video packet transmission and overhearing algorithm at a node.

(not packet-level) requiring thus significant amount of execution time. Regarding the lower layer parameters we assume a channel bandwidth of $W$=20 MHz, while the same Rayleigh fading path loss model was used for all the channels. Our assumptions in this case include a frequency-flat fading wireless link that remains invariant per transmitted PHY frame, but may vary between simulated frames. The noise over the wireless spectrum is additive white Gaussian noise (AWGN) with the variance of the noise to be $10^{-9}$ Watts/Hz at every node/link. The average transmitter channel SNR depicted in the horizontal axis of all the figures was assumed to be the same for all the links but it varied independently during each channel realization.

For the video part of the simulation, we examine the performance of different system configurations. The first class of algorithms determines how the network treats packets: The system named FIXED uses one specific relay for each client and it is the baseline system. Our overhearing and forwarding algorithm is named video packet overhearing (VPO). We also implemented opportunistic network coding (NC) of the MORE scheme [9], that moves one step further and encodes packets at the relays. For the NC scheme we limited the feedback messages between the nodes to be at most $5\%$ of the total bandwidth used. The previous packet processing algorithms were tested both for a system that did not employ distortion optimization namely NoOpt, and a



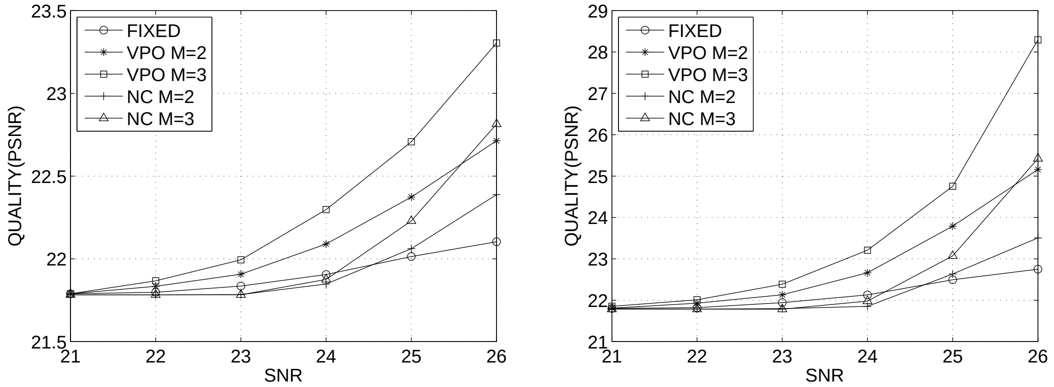
(a) NoOpt (b) Opt

FIGURE 2.5: Average PNSR vs. the average channel SNR for system without ARQ. $d_s = 5$ seconds.

system that employed the RD optimization step and is denoted as Opt. The utility optimization was exercised for the duration of 10 GOPs. The media content used in the experiments consists of the CIF sequences MOTHER & DAUGHTER and FOREMAN that were compressed using the SVC H.264 codec [18] at the rates of 203 kbps and 328 kbps, respectively. For the experiments with one video flow the sequence MOTHER & DAUGHTER was tested while both of them were used the two-flow experiment. A number of 300 frames of each sequence were encoded at a frame rate of 30 fps using the following frame-type pattern IBBBP..., i.e., there are three B frames between every two P frames. The GOP size was set to 32 frames. Also, the startup/playback delay of the video presentation at every node is denoted as $d_s$. In all the figures, the results correspond to the average PSNR enjoyed by a all relays and the destination for the duration of 300 seconds.

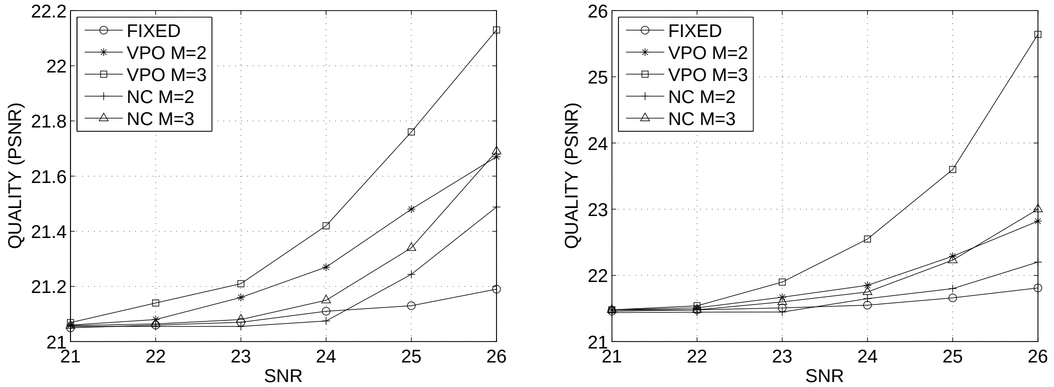
### 2.6.1 Results for One Video Flow

Results are shown for the NoOpt system in Fig. 2.5(a), while results for the Opt system are shown in Fig. 2.5(b). As expected the increased number of small-cell relays results in higher capacity and eventually higher utility/quality. We notice that for the Opt system the rate of increase of the average utility is higher as the channel quality is improved when compared with the previous case of NoOpt. The reason is that when the channel is poor, then more critical video packets are not delivered to the end user while when the PHY performs well then more PHY packets are successfully decoded and so more high-impact video units are played back. This result clarifies the first main point we want to come across from this paper. That is, distortion-optimized streaming is even more important to be used when the channel is good and not so much when the channel is bad.



(a) NoOpt (b) Opt

FIGURE 2.6: Average PNSR vs. the average channel SNR for system with ARQ. $d_s = 10$ seconds.



(a) NoOpt (b) Opt

FIGURE 2.7: Average PNSR vs. the average channel SNR for TWO flows and a system without ARQ $d_s = 15$ seconds.

We also evaluated a system where we enabled the ARQ mechanism that typically exists at the link layer (IEEE 802.11, LTE, WiMaX). In this case we also set $d_s = 10$ seconds to accommodate for the impact of the ARQ mechanism. We see now that the startup delay is increased, and the retransmissions are also increased, this has considerable impact on the quality of the Opt system. The reason is that in this case the important video packets are transmitted from the source according to the result of the optimization step. When they are passed to the link layer, they are already classified as the most important packets that should be combined with ARQ. Thus, it is critical for avoiding explicit cross-layer interaction with a scheme like Unequal Error Protection (UEP) to perform distortion-optimized rate allocation at the source. In order to improve the impact of ARQ decisions on the NoOpt system one would normally have to use ARQ for providing UEP to the video packets.

### 2.6.2 Results for Two Video Flows

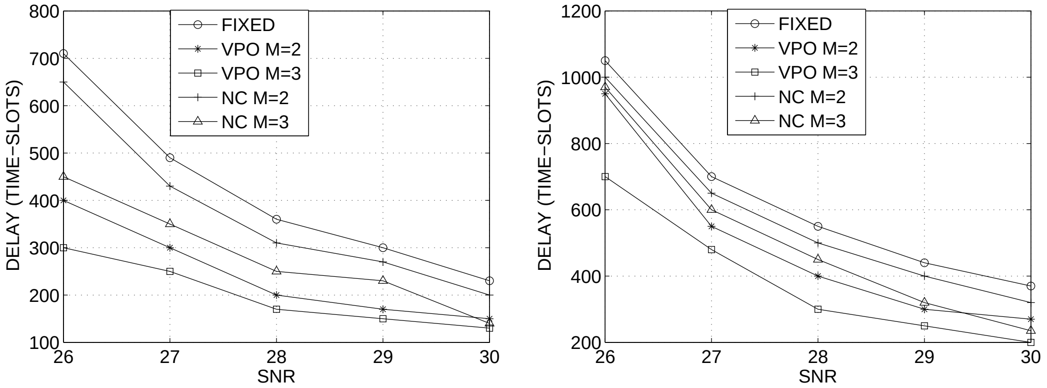
Results for two video flows can be seen in Fig. 3.4. We also configured a slightly higher startup delay due to bandwidth splitting across the two users. As it can be seen also in Fig 3.4(b), the results have the same form as the results for one flow. As the channel quality is improved for the Opt System when compared with the previous case of NoOpt and the number of small-cell relays are increased, the rate of increase of the average utility is higher.

### 2.6.3 Comparison with NC

In all the above results, we also present results for network coding that is employed at the relays. NC offers some benefits only for relatively high SNR but even in this range the impact is not significant. The reason is that in this channel SNR regime the majority of wireless packets are received by all the relays and so there is no NC benefit. On the other hand in the low SNR regime the benefit of NC is similarly limited because the packet coding opportunities are less due to the high PER. This situation is true also for all the Opt systems as it can be seen for example in Fig 3.4(b) while the performance differences of VPO over NC are even bigger. Thus, the important conclusion in that overhearing implemented through a simple protocol like VPO is enough for making distortion-optimal streaming decisions in this scenario where multiple relays exist and the flow is unicast.

### 2.6.4 Delay Results

Results for the end-to-end delay of the system without Opt can be seen in Fig. 3.5. The benefit of VPO with more than one relay, is attributed to the lower packet error rate for individual packets and the reduced need for re-transmissions. However, when no re-transmissions are allowed, still the delay of VPO is less as the number of relays is increased because of the higher throughput that can be achieved.



(a) NoOpt without ARQ

(b) NoOpt with ARQ

FIGURE 2.8: Total delay vs. the channel transmit SNR for a system without optimization.

# Chapter 3

# Video- Aware Relay Selection in Single-Carrier and OFDM Wireless Systems

## 3.1 Introduction

High quality video streaming in wireless networks is one of the hottest mobile applications today. The widespread adoption of mobile devices that are capable of handling sophisticated and high data-rate wireless communication algorithms is propelling this demand. The video traffic explosion in wireless networks is expected to continue with rapid increases [19]. To address this massive demand for high quality video, mobile network operators have several options in their arsenal. One is the deployment of relay nodes at different locations within the coverage area of a single cell. Relays can be deployed in small-cell configurations in order to process the received signal from the base station (BS) before forwarding it to the destination (Fig. 3.1). This type of cooperation among different network nodes provides a flexible alternative to the use of multiple antennas in order to create diversity for the transmitted signals and lead eventually to higher throughput. Although cooperative diversity with relays has been investigated considerably from a theoretical perspective, in the immediate future the prospects of being implemented are better than ever precisely because of the high demand for increased bandwidth and coverage. Many standards like LTE-Advanced and WiMaX, support relay-based transmission modes that have been shown to be practical [13].

Wireless cooperative transmission of video streams has been studied in the literature considerably the last few years but the term *cooperative transmission* may span techniques applicable at different layers of the protocol stack. The case of layered encoded video in conjunction with the novel PHY technique of distributed space-time coding (DSTC) was studied in [5]. Distributed space-time codes were employed in that work in order to improve the decoding of the PHY symbols when multiple receivers are involved. One important issue that must be addressed in

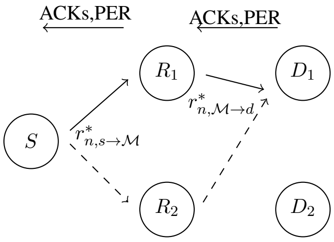


FIGURE 3.1: System model that includes the source, a number of relays and destinations. Here, only the packet flow towards $D_1$ is shown to avoid clogging the figure. The dashed lines indicate the overheard packets from a helping relay. The ACKs are transmitted on a hop-by-hop links basis only, while the source receives information for the average PER/throughput at each destination.

DSTC is that the relays must transmit simultaneously which means perfect synchronization is required. Furthermore, the signal diversity benefits of DSTC can also be achieved in a distributed network with simpler protocols [20] according to which it is enough to select the relay with the best channel. An important observation is that the previous schemes focus on using a cooperative transmission approach for increasing the reliability of packet transmissions that eventually translates to higher throughput/video quality. However, the potential performance impact of embedding video-awareness into the relay selection process has not been investigated very thoroughly. Recently, there are some works towards this direction. In [21] the authors proposed the cooperative relay selection by modeling the system as an Markov Decision Process (MDP). The communication model considers only uplink transmissions towards an access point (AP). Even though the approach minimizes information exchange between networks nodes, still there is a need for message passing rounds between the relays and the AP. *Our first contribution in this chapter is that we consider optimized relay selection for each individual video packet while this scheme requires no information exchange between the relays and any other node.*

Further study of the problem reveals that it is unexplored when we consider relays that use advanced and real-life modulation schemes like orthogonal frequency division multiplexing (OFDM). Research works that propose embedding video-awareness in OFDM systems do not consider the case of cooperative transmission based on relays. In [22] the authors considered uplink streaming over OFDM. In [23, 24] the authors considered the problem of OFDM subcarrier power allocation for wireless real-time encoded video in a downlink scenario and without relays. Finally, another aspect of the the cross-layer video-aware OFDM schemes that can be found in the literature is that the power allocated to the subcarrier is independently allocated from the content of the video packet that is transmitted. For example in [25, 26] the authors considered an ordering of the subcarriers depending on the channel fade. *Thus, our second key contribution in this chapter is first that we consider relay selection for an OFDM system and second that we execute sub-carrier power allocation that is aware of the video packet content.*

In this chapter, we target the optimized video delivery in a wireless cooperative network (Fig. 3.1). We propose a fully distributed relay selection algorithm that incorporates into the relay selection process the video content of the packet to be transmitted. Our scheme first selects the best relay from a set of $M$ available relays and then uses this ”best” relay for cooperation between the source and the destination. Our method is *fully distributed* and requires no topology information and exchange of special messages between the relays. Only passively collected local measurements of the channel state is used at the relays. This approach is also extended for an OFDM modulation scheme. In this later case besides the video aware relay selection, we jointly optimize the allocated power to each subcarrier depending on the video content of the packet that requires transmission.

## 3.2 System Model and Assumptions

**Network Model:** We consider again the unicast streaming of a set $S \triangleq \{1, 2, .., n, .., N\}$ of $N$ pre-compressed and packetized video streams from a single source node to $N$ destination nodes that each one is interested in a specific video stream. Besides the source and the destinations, the network also includes $M$ relays that are not the consumers of the video streams but their task is to aid by forwarding traffic to the destinations as seen in Fig. 3.1. We assume that the $M$ neighboring relays are densely deployed as shown in Fig. 3.1 and they can overhear each other. Note here that it may be that $M > N$.

**Video source rate adaptation and Packet Transmission:** The source multiplexes the packets of different flows and broadcasts them to the relays. The source transmits video flow $n$ at rate $r_n$. We apply rate adaptation in order to calculate the streaming rate $r_n$ that is optimal given the end-to-end available data rate [27]. To accomplish that, the packet error rate information is periodically collected at the source (e.g. through RTP messages) and then the source executes a rate allocation algorithm to derive the optimal $r_n^*$ . Since we perform rate adaptation/allocation at the source based on information for the complete end-to-end channel, we know that all the packets that are transmitted from the source should reach the destination and not be dropped. Therefore, the relays know that they must transmit all the packets in their FIFO buffer, e.g. this behavior is similar to employing TCP.

**Video Content Model:** The rate-distortion (R-D) information associated with packet $i$ is contained in each packet header and it consists of its size $\Delta R(i)$ in bytes, and the importance of the packet for the overall reconstruction quality of the media presentation denoted as $\Delta D(i)$ [1]. In practice, $\Delta D(i)$ is the total increase in the mean square error (MSE) distortion that will affect the video stream if the packet is not delivered to the client by its prescribed deadline [28].

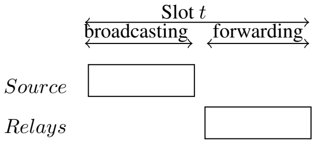


FIGURE 3.2: Behavior of the cooperative protocol in the time domain. Time is slotted and each slot is separated in two phases. Which relay will transmit and what packet are the targets of our optimization in this chapter.

**Channel Access:** The channel access scheme employed by the source node/relays follows a simple structure widely adopted in cooperative networks. The basic cooperative protocol separates a single time slot into two phases (see Fig. 3.2). The source node broadcasts in the first phase. During the broadcast phase the $M$ relays also overhear this transmission. Next, there is one forwarding phase from a relay to destination node. The relay that will obtain access to the channel and transmit, is selected in a distributed fashion as we will describe later in this chapter.

**Channel Model and PHY Modulation:** At the PHY we first assume the use of single-carrier (SC) Phase Shift Keying (PSK) modulation scheme. All the channels are considered to be narrowband block-fading Rayleigh. The channel coefficients are quasi-stationary, that is they remain constant for the coherence time of the channel (slow fading). We denote the channel from the $s$-th source to the $r$-th relay as $h_{s,r}$, and the channel from the $r$-th relay to destination $d$ as $h_{r,d}$. Additive white Gaussian noise (AWGN) with zero mean and unit variance is assumed at the relays and the destinations. We also assume that each transmitter employs a type of ARQ (e.g. hybrid ARQ) that is typical in cellular and WLAN standards. We also consider OFDM modulation. In the OFDM case the bit sequence that constitutes a single packet is de-multiplexed into each of the used subcarriers. We also assume CSIT is available for both the SC and OFDM modulation schemes.

## 3.3 Packet Overhearing at Relays

With our system, when a packet is broadcasted from the source node it may be received at an arbitrary number of relays. If the relays are left without coordination they may transmit the same packet to the same destination. To avoid duplicate packet transmission we propose a simple protocol[1]: When a relay forwards a packet to the next hop destination, the remaining relay nodes also overhear this DATA transmission and its acknowledgement through the ACK. By following this approach, the neighboring relays know that if they have the same packet in their buffer, there is no need to transmit it in the next time slot that they obtain the channel. Instead, they discard it if they also overhear this ACK. In case a packet transmission from a relay fails, this is detected by the lack of an ACK message. So all the relays retain the lost

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[1] We have more details in our technical note that can be found in www.inf.uth.gr/ anargyr

packet since any one of them may transmit it in the next opportunity they have. Therefore, this simple overhearing algorithm allows the relays to forward uniquely each video packet to the next hop without exchanging detailed buffer maps regarding the data they have, and with the minimal implementation requirements.

## 3.4 Video-Optimized Distributed Relay Selection in a Narrowband Channel

In the case of digital wireless transmission over slow fading channels when the channel is in deep fade the transmitter must employ channel coding and interleaving over many channel coherence periods in order to achieve the ergodic rate of the channel [2]. However, the previous approach introduces significant delays for real-time data transmission. The fundamental approach that addresses this problem is diversity, i.e. the use of many independently transmitted copies of the same information. Cooperative diversity with relays is such a method and we will use it in this paper. Cooperative diversity can be applied in conjunction with relay selection protocols that are responsible for selecting the relay with the best channel. This approach has been shown to be effective in maximizing the diversity benefits even without the use of STC [20]. We use cooperative diversity but *we do not only want to identify the optimal relay but also the optimal packet and relay combination from all the available relays* and all the received packets at the relays. The key observation is that because of the broadcast transmissions from the source, the same packet may be available at many relays while the relay that has the best channel towards a destination may not have received an important video packet.

### 3.4.1 Problem Formulation

The last observation that motivates this work must be converted to a concrete problem formulation. The intuition behind our problem formulation is based on the interpretation of fading events on the channel capacity. More specifically, for a slow fading channel with fading gain $h$, transmission power $P$, AWGN with zero mean and variance $N_0$, and bandwidth $W$, the parameter $W \log_2(1 + \frac{P|h|^2}{N_0})$ can be seen as the number of bits/sec that the channel can reliably transmit [2]. Our description of the optimization problem further clarifies the practical use of the previous observation. Let us denote the utility and the length of the current HOL packet at relay $r$ as $\Delta D_r$ and $\Delta R_r$ respectively. Let also $\vec{x}$ be a vector that contains the activation variables for the involved relays, i.e. $x_r$ is 1 if relay $r$ is activated in the current slot. Thus, the problem of distortion-optimized relay selection over a narrowband fading channel is defined as follows:

$$\text{OPT1}: \quad \max_{\vec{x}} \sum_{r=1}^{R} x_r \frac{\Delta D_r}{\Delta R_r} \log_2 \left(1 + \frac{P|h_{r,d}|^2}{N_0}\right)$$

$$x_r \Delta R_r \leq \log_2 \left(1 + \frac{P|h_{r,d}|^2}{N_0}\right) \text{ (C1)}$$

$$\sum_{r=1}^{R} x_r = 1,$$

The rationale of this form of the optimization objective is that the utility of the ”best” packet is multiplied by the instantaneous rate of that particular relay and the result is a scaled utility metric. This approach couples first the impact of relay selection through $x_r$, and the utility of a specific packet $\frac{\Delta D_r}{\Delta R_r}$, with the instantaneous achievable rate of the Rayleigh slow fading channel. Consider for example two relays with $h_{1,d} < h_{2,d}$. Assuming an optimal power allocation for $r = 1$ of $p_1^*$ then with an optimal AWGN code this relay can reliably communicate at a rate $\log_2\left(1 + \frac{p_{r,t}^*|h_{r,d}|^2}{N_0}\right)$ bits/sec. Even if the second relay can reliably communicate more bits, the result is that if a packet of high utility is available at the first relay ($r$=1) this specific packet is selected for transmission. A critical observation is that when a packet to be transmitted has size $\Delta R$ that is higher than the available channel rate, then we cannot reliable communicate this number of bits. This is captured by the first constraint of problem OPT1. For a Rayleigh fading channel a high or low value for $h$ is usually translated to the so-called outage event.

### 3.4.2 Distributed Solution with Video-Aware Channel Access and Relay Selection

Now the first question is how to solve this LP in a distributed fashion. Calculating the optimal $\vec{x}^*$ would be easy to be performed in a centralized fashion but this is not possible in our case since each relay knows only its local channel estimate $h_{r,d}$. Relay selection is a typical issue that has to be addressed in cooperative wireless networks. In several works this problem has been addressed with simple distributed solutions [20, 29].

In our system, it is implemented as follows. First, when the relay transmits a packet, and the destination transmits an ACK, all the relays estimate the channel towards the destination. Based on the wireless channel reciprocity property the channel gain serves as a good estimate of the forward channel from the relay to the destination [2]. To solve OPT1 in a distributed fashion, a relay calculates the scaled utility, and it accesses the channel by setting a specific timer depending on this value. In particular it is set equal to

$$TO_r = \lfloor \frac{1}{\frac{\Delta D_r}{\Delta R_r} \log_2(1 + \frac{P|h_{r,d}|^2}{N_0})} \rfloor, \tag{3.1}$$

This happens only when C1 is satisfied. In any other case the relay does not contend for the channel and does not set this timer. Now in the case that C1 is satisfied and the relay has set the timer as described before, the result is that this timer will expire first for the relay that has calculated a higher scaled utility value. Fig. 3.3 depicts this channel access scheme that is aware of the utility of the video packet that is transmitted. *This is the novel aspect of our approach: The optimal relay is not the one that simply has the best channel $h$, but the one that has the most important media packet in its FIFO transmission buffer, and it can also transmit it reliably without the channel being in outage.*

## 3.5 Video-Optimized Distributed Relay Selection for OFDM Modulation

### 3.5.1 Problem Formulation

In our next problem formulation we consider the case that that the modulation scheme is OFDM. In this case we have to identify the optimal relay and also the optimal power for each subcarrier that the relay uses. Given a total power budget $P$ Watts for each specific relay, the relay will need to decide what is the power it must allocate to the $s$-th subcarrier if it is activated during a number of slots. Thus, we have:

$$
\begin{aligned}
\text{OPT2a}: \quad & \max_{\vec{x},\vec{p}} \sum_{r=1}^{R} x_r \frac{\Delta D_r}{\Delta R_r} \sum_{s=1}^{S} \log\left(1 + \frac{p_{r,s}|h_{r,d}|^2}{N_0}\right) \\
\text{s.t.} \quad & \sum_{s=1}^{S} p_{r,s} \leq P, \forall r \in \mathcal{R} \text{ (C1)} \\
& \sum_{r=1}^{R} x_r \Delta R_r \leq \sum_{r=1}^{R} x_r \sum_{s=1}^{S} \log\left(1 + \frac{p_{r,s}|h_{r,d}|^2}{N_0}\right) \text{ (C2)} \\
& \sum_{r=1}^{R} x_r = 1 \text{ (C3)} \\
& x_r \in \{0,1\}, p_{r,s} \geq 0, \ \forall r \in \mathcal{R} \text{ (C4)}
\end{aligned}
$$

In this problem formulation we see that the rate that can be achieved depends on the channel gain of each subcarrier $s$ and the power allocated to it. In the utility function of problem OPT2a, the goal is to select the ”best” relay among all of them given this additional degree of freedom. The first constraint C1 ensures that the power allocation to the $S$ total subcarriers for each relay will not overcome the total power budget $P$ for this relay. The second and third constraints C2, C3 serve the same role as the first and the second constraints of the problem OPT1 for the single-carrier narrowband relay selection case. In particular, these constraints ensure that relay $r$ can reliably communicate with the destination node and that only one relay is used for transmission in a specific time slot.

**Solution.** To solve the previous problem we note first that there are integer and continuous variables. Thus, it is a non-convex and NP-hard problem to solve. However, we can decouple it into a convex and linear subproblems following the approach in the previous section. We can solve it in three steps as follows.

**Step 1:** The relay $r$ selects an optimal power allocation by solving the equivalent problem OPT2b we define next:

$$\begin{aligned} \text{OPT2b}: \quad & \max_{\vec{p}} \sum_{s=1}^{S} \frac{\Delta D_r}{\Delta R_r} \log\Big(1 + \frac{p_{r,s}|h_{r,d}|^2}{N_0}\Big) \\ & \sum_{s=1}^{S} p_{r,s} \leq P, \forall r \in \mathcal{R} \\ & p_{r,s} \geq 0,\ \forall r \in \mathcal{R} \end{aligned}$$

This convex problem formulation finds the best subcarrier power allocation that considers however the utility of the HOL packet $\frac{\Delta D_r}{\Delta R_r}$. For solving this problem we form the Lagrangian of the convex problem OPT2b:

$$L_r(\lambda, \vec{p}) = \sum_{s=1}^{S} \frac{\Delta D_r}{\Delta R_r} \log\Big(1 + \frac{p_{r,s}|h_{r,d}|^2}{N_0}\Big) - \lambda(\sum_{s=1}^{S} p_{r,s} - P),$$

The rationale of this approach is that the relay tries to allocate the power by taking into account the utility of the packet. The result is a variation of the well-known water-filling that leads also to a no-primal power allocation. The final result from the application of the K.K.T. conditions is for relay $r$ is

$$p^{*}_{r,s} = \Big(\frac{\Delta D_r/\Delta R_r}{\lambda^{*}} - \frac{N_0}{|h_{r,d}|^2}\Big)^{+}$$

*What the above result means is that the optimal power that is allocated from the relay for the transmission of the HOL packet depends on its utility.* The next packet that will be transmitted in a subsequent slot will be with a power level that depends on the utility of the next best packet in the buffer.

**Step 2:** In the next step, for the calculated solution the relay checks if the packet length complies with the rate constraint (defined as second constraint C3 in OPT2a. If this is true then it proceeds to step 3. Otherwise the relay does not contend for the channel since it cannot ensure reliable communication even with an optimal power allocation.

**Step 3:** Finally, the relays in a distributed fashion contend for the channel similarly with the narrowband channel case, i.e. by setting the timer with the scaled value, as we described above.

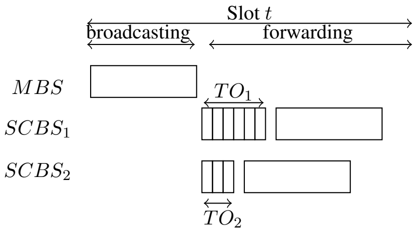


FIGURE 3.3: The timer of the relay with the packet of the highest scaled utility expires earlier obtaining thus first access to the channel.

In this case the scaled utility depends on the achieved OFDM rate over all the subcarriers.

## 3.6 Performance Evaluation

In this section, we present a comprehensive evaluation of the proposed algorithms comprising our framework through simulations. We have implemented both the PHY outlined in Section 3.2, the video streaming system, and the overhearing and relay selection algorithms in Matlab. The number of relay nodes $M$ is kept small since the simulator operates at the PHY symbol level (not packet-level) requiring thus significant amount of execution time. Regarding the lower layer parameters we assume a channel bandwidth of $W$=20 MHz, while the same Rayleigh fading path loss model was used for all the channels. Our assumptions in this case includes a frequency-flat fading wireless link that remains invariant per transmitted PHY frame, but may vary between simulated frames. The noise over the wireless spectrum is AWGN with the variance of the noise to be $10^{-9}$ Watts/Hz at every node/link. The average channel SNR depicted in the horizontal axis of all the figures was assumed to be the same for all the links but it varied independently during each channel realization. We also enabled the ARQ mechanism for the evaluation of the above systems. These ARQ feedback processes are assumed without error.

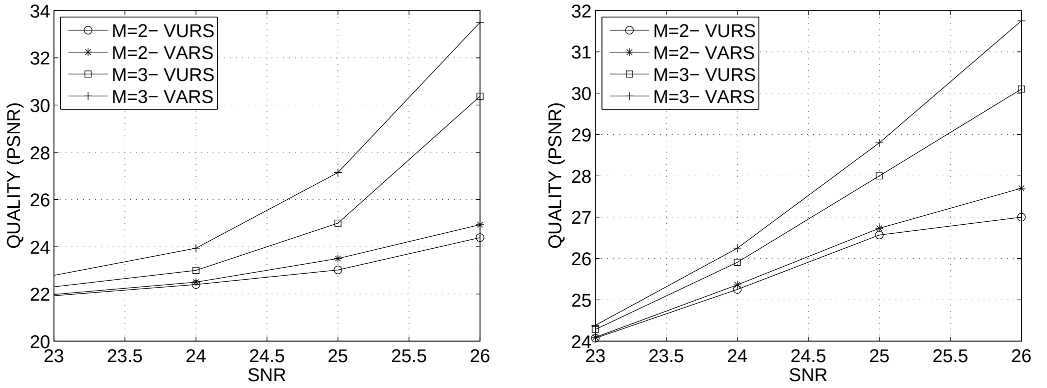
The rate allocation at the source was exercised for the duration of 10 GOPs. The media content used in the experiments consists of the CIF sequences MOTHER & DAUGHTER and FOREMAN that were compressed using the SVC H.264 codec [18] at the rates of 203 kbps and 328 kbps, respectively. Each video frame was packetized in one slice. For the experiments with two video flows both of them were used. A number of 300 frames of each sequence were encoded at a frame rate of 30 fps using the following frame-type pattern IBBBP. The GOP size was set to 32 frames. Also, the startup/playback delay of the video presentation at every node is denoted as $d_s$. In all the figures, the results correspond to the average PSNR enjoyed by a all relays and the destination for the duration of 300 seconds.

We examine the performance of different system configurations. The first algorithm named video unaware relay selection (VURS) and uses a relay selection scheme that takes into account only the best channel $h_{r,d}$ between the relays and the destination [20]. Our scheme is named video aware relay selection (VARS). For the simulation of OFDM system we also used a system that is video unaware and it executes optimal power allocation according to the classic water-filling approach. The previous system is compared to our VARS OFDM-based system. We also examined the effect of using a different number of subcarriers.

### 3.6.1 Results for a Single Carrier System

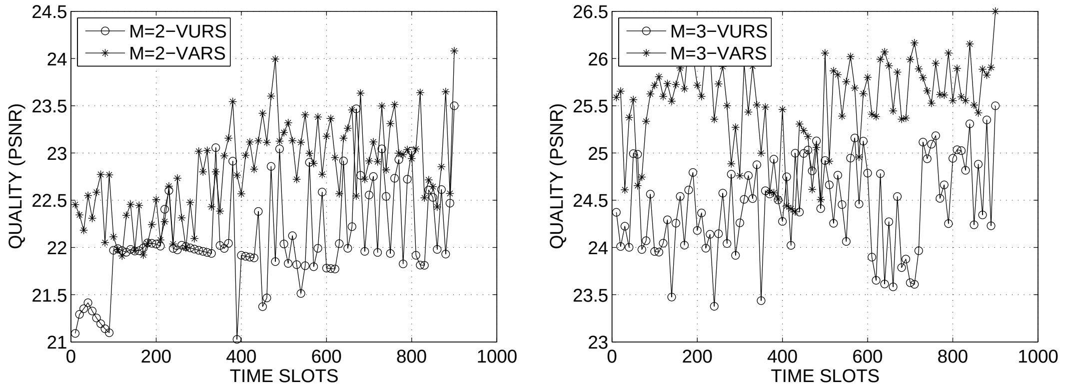
In this section, we study the video quality that can be achieved with all the systems we described before. Results for two video flows can be seen in Fig. 3.4(a).We also configured a slightly higher startup delay of 5 sec due to bandwidth splitting across the two users. For lower values of the average channel SNR the relay selection schemes show almost the same behavior. This is because in the lower SNR regime the channel is in outage frequently and a packet cannot be transmitted reliably with any scheme. On the other hand, in the higher SNR regime the benefit of VARS is quite significant when compared to the VURS. This means that when the channel quality is good, the utility of the video packet is a crucial factor for the distributed relay selection. In particular in this case several relays might have a good channel and so many of them can send a video packet reliably. However, only VARS ensures that this is a packet that has the highest utility. We also evaluated a system where we enabled the ARQ mechanism that typically exists at the link layer (IEEE 802.11, LTE, WiMaX) in Fig. 3.4(b). In this case we also set $d_s = 10$ seconds to accommodate for the impact of the ARQ mechanism. We see now that the startup delay is increased, and the retransmissions are also increased, this has considerable impact on the quality of the both systems. However, the performance gain of the proposed scheme is even higher than the previous case scenario. We also measured the real-time value of PSNR at the destination for the case of two and three relays. A value for the average channel SNR of 25dB was used. In Fig. 3.5 we see that indeed our scheme for VARS can achieve the best real-time video quality at the duration of time.

Another key benefit of our approach is that it takes into account the precise utility of each video packet. In this next experiment we used two different video sequences (FOREMAN and MOTHER & DAUGHTER) that have different rate-distortion characteristics. We also enabled the ARQ mechanism and we used $M = 2, 3$ relays. As it can be seen in Fig. 3.6 , we can have significantly better results for the video sequence that has packets of higher utility value (in this case FOREMAN). Recall that Foreman has significant motion and so it has packets with higher utility.



(a) ARQ (b) No ARQ

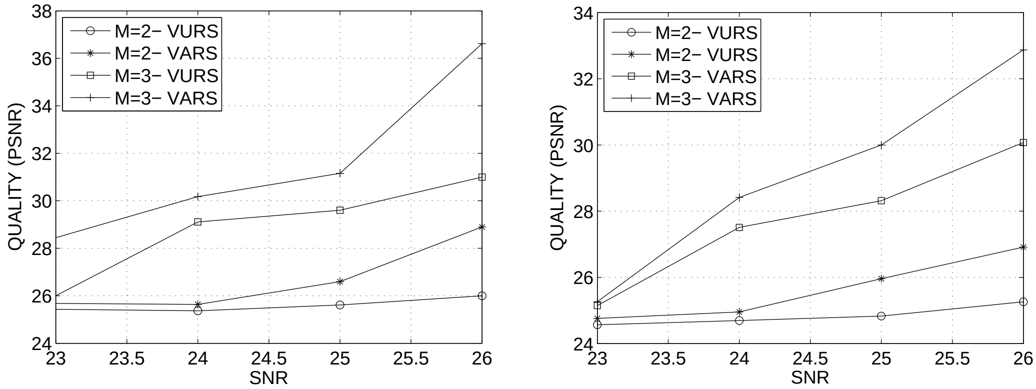
FIGURE 3.4: Results for the streaming of the two flows MOTHER & DAUGTHER and FOREMAN.



(a) M=2 (b) M=3

FIGURE 3.5: Real-time PSNR results for the streaming of the two flows MOTHER & DAUGTHER and FOREMAN.

Last, we can compare the quality of two specific pictures/frames of a video that the client will watch with the video aware relay selection scheme (VARS) and with the video unaware relay selection scheme (VURS). For this simulation , we used M=3 relays and the FOREMAN video sequence. We selected two frames for comparison that has been transmitted to the destination with both of the above two schemes. The frames that were selected are the 50 and 270 of FOREMAN video sequence. As can be seen in Fig. 3.7 and in Fig. 3.8, with the video aware scheme the quality is quite better for both of two frames than that with the video unaware scheme.



(a) FOREMAN (b) MOTHER & DAUGHTER

FIGURE 3.6: Comparison of FOREMAN and MOTHER & DAUGHTER

(a) VARS (b) VURS

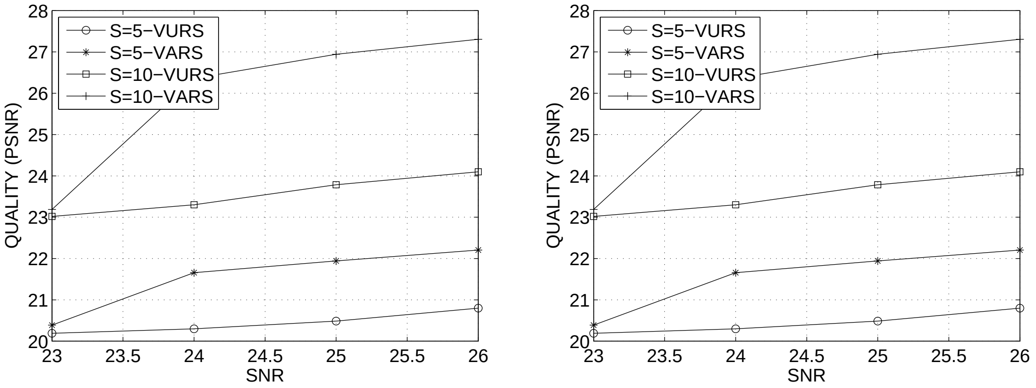
FIGURE 3.7: Comparison of (VARS) with (VURS) for frame 50 of FOREMAN

### 3.6.2 Results for OFDM

In our OFDM experiments, we used M=2,3 relays as intermediate nodes between the source and the destinations while we did not enable the mechanism of ARQ. We also evaluated the effect of different number of subcarriers and more specifically the cases of S=5, and S=10. Generally, with an increase in the number of subcarriers that each relay uses, a smaller PER can be achieved from the relays to destination leading to better quality of video at the destination node. In any case, as it can be shown in Fig. 3.9 with our video aware scheme we observed significant improvement at the quality of video at the destination node compared to video unaware OFDM power allocation approach.

(a) VARS (b) VURS

FIGURE 3.8: Comparison of (VARS) with (VURS) for frame 270 of FOREMAN



(a) M=2 (b) M=3

FIGURE 3.9: Comparison of the OFDM systems with $S = 5$, and $S = 10$ subcarriers

# Chapter 4

# Conclusions- Future Work

## 4.1 Conclusions- Future Work

Summarized, we initially presented an RD-based utility optimization framework for video streaming in densely deployed small-cell wireless relay networks at the first chapter. The wireless network employs overhearing of packets to exploit the natural diversity that the wireless network offers. Our first contribution is to demonstrate for this type of emerging wireless network it is enough to allow overhearing of video packets and employ our distortion optimized streaming approach instead of employing more sophisticated coding techniques. Our second contribution is on the design of an overhearing algorithm that allows the implementation of the previous rate allocation approach in a small-cell wireless relay network with minimal overhead. The performance results showed the significant performance benefits of the proposed scheme over a number of alternatives. It was also shown that the case of multiple video can be benefited even more from the proposed approach.

Then, at the second chapter we presented a distributed relay selection algorithm for fading channels that is engineered both for SC and OFDM modulation systems. Our motivating observation is the broadcast nature of the wireless channel that allows the same packet to be available at many relays while the relay that has the best channel towards the destination may not have received an important video packet. To address this issue we proposed an algorithm that selects both the optimal relay and the packet so that the video quality is maximized. It is important to be mentioned that our algorithm for relay selection takes also into account the power budget of its relay. So it can not be selected consecutively the same relay for transmission and it can be selected only if its power budget has not been depleted. The above observation is very important for implementation in real systems (WiFi, LTE). Our second contribution is the development of an approach that selects not only the optimal relay and packet combinations but that also allocates optimally the transmission power to each subcarrier of an OFDM system. Significant performance improvements were observed for all the proposed systems.

So, the basic observations of this master thesis are below. Firstly,if we want to transmit different video flows from source nodes to destination nodes, having a group of relays at different locations within the coverage are of a single cell and they can 'overhear' the other transmission, our algorithm 'Packet Overhearing' is more convenient for optimization of quality of video than others more complicated methods, such as Network Coding. Secondly, the method of our distributed video- aware relay selection, without coordination among the relays can optimize additional the quality of video instead of distributed space time coding methods (DSTC) that was studied and it has been approved that needs perfect synchronization among the relays.

For future work,we could also consider the above "video- aware" relay selection approach combined with more advanced error protection algorithms for video streams like UEP. Furthermore, it is very important the channel and system model parameters that analysed above to be tailored to specific systems like WiFi and LTE. Last, we could also consider the above approaches for a multi- hop relay based wireless network. But the 'key' observation that we must take into account is that increasing the number of hops the quality of video significantly decreased.

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