A Cooperative Protocol for Video Streaming in Dense Small Cell Wireless Relay Networks

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Abstract

The small-cell wireless network (SCN) paradigm is based on the deployment of low-power small cells close to the user so that spatial re-use is increased. Small cell base stations (SCBS) can be connected either with a wired or wireless backhaul link to the core network. However, since these SCBSs are expected to be deployed in significant numbers [1], the increased density creates new problems but also optimization opportunities. In this paper we work towards the full exploitation of the broadcast advantage that dense SCNs offer in order to improve the video quality of unicast streaming applications.

To accomplish our goal we design a protocol that exploits the broadcast channel in the neighborhood of each small cell by using the SCBSs opportunistically as a relay stations. Each SCBS can overhear packet transmissions both from the macro BS (MBS) and also from other SCBSs in its neighborhood. Furthermore, since a packet may be available at multiple SCBSs, we propose an algorithm for optimized relay selection that takes into account the content of each specific video packet. This algorithm selects jointly the optimal small cell relay and video packet for forwarding. Both the overhearing protocol and the relay selection algorithm use only passively collected information and require no explicit message passing. The evaluation of the two proposed sub-systems shows significant performance improvements under different key system configurations for the video content, the number of neighboring SCBS, and the type of the backhaul connection.

1 Introduction

High quality video streaming in wireless networks is one of the most popular mobile applications today. The widespread adoption of mobile devices that are capable of handling sophisticated video processing and high data-rate wireless communication algorithms is propelling this demand. The video traffic explosion in wireless networks is expected to accelerate even more the next few years [2]. To ensure high quality video streaming there is a need for more bandwidth. Even after compression, video is bandwidth-hungry and delay-sensitive. Thus, there is no fundamental way to bypass this problem except by providing more bandwidth. To ameliorate this problem in cellular networks, small cell base stations (SCBS) or small cell relay stations are deployed closer to the user in order to increase network capacity and spatial coverage respectively.[1] The envisioned cellular network configuration includes several SCBS with overlapping coverage, while the typical macro base station (MBS) provides umbrella coverage [1, 3]. Thus, besides the single SCBS node that a user may be associated to, neighboring SCBSs will also probably be reachable by the same user (See our topology in Fig. 1). But the dense deployment of these wireless networks can be exploited with even smarter ways so that they can increase the capacity, decrease delay, and minimize susceptibility to channel variations if they operate as relays. Although cooperative diversity with relays

[1]Note that the roles of a SCBS and relay station can be collocated in the same physical device.

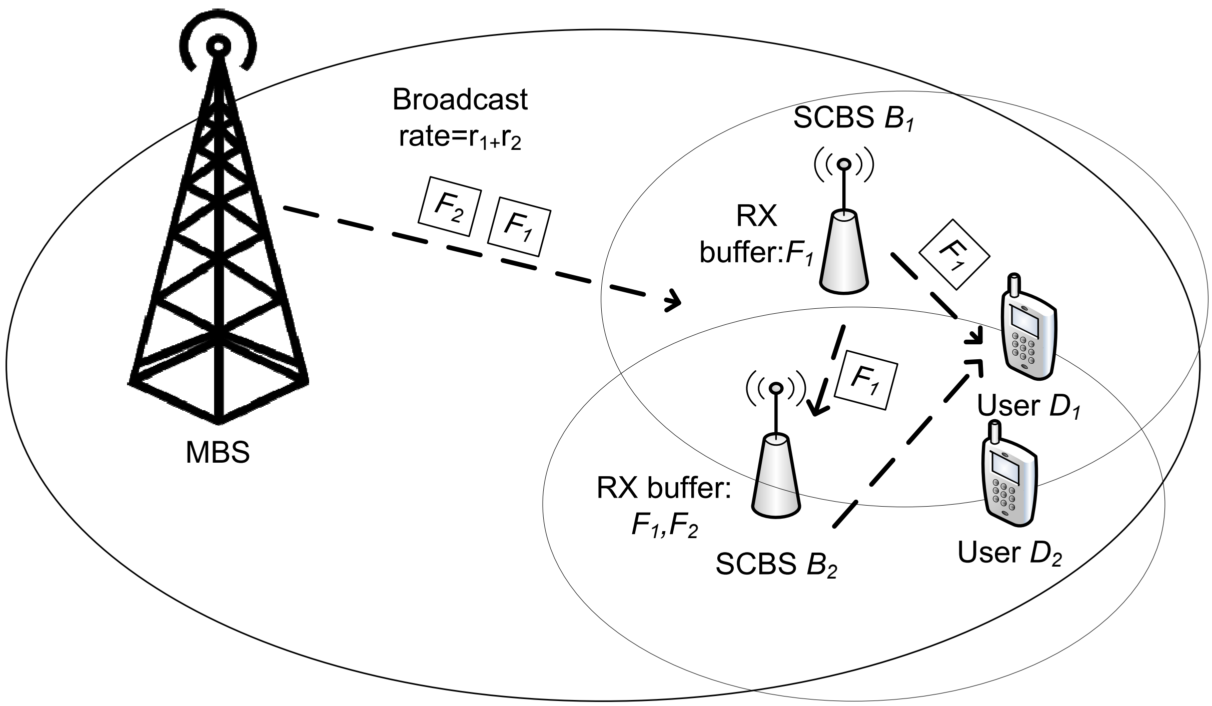


Figure 1: In the small-cell network topology adopted in this paper, each user receives a different video flow through the SCBS that is associated. In the wireless backhaul case both SCBSs can overhear packets from both video flows. The video flow F_1 is depicted to avoid clogging the figure.

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-A support relay-based transmission modes that have been shown to be practical [4].

In this paragraph we will try to highlight potential optimization opportunities in *dense SCNs* with simple examples. Consider the case of a wireless backhaul connection between the MBS and the SCBSs as illustrated in Fig. 1. The transmissions from the MBS can be overheard from the two target SCBSs within the cell. Now the question that has to be answered is which of the two SCBSs will transmit a packet from the first flow since they have both received it. Also assume that SCBS B_1 has been granted access to the channel and transmits the packet (according to one of the algorithms that we will propose). Due to the proximity of the two SCBSs, SCBS B_2 cannot transmit simultaneously with SCBS B_1. However, this does not prevent it from overhearing the transmission of packets from its neighbor, and remove it from its local buffer when user D_1 acknowledges it (this is handled by the second algorithm we propose in this paper). The same situation will occur if more SCBSs are deployed close to SCBS B_1, i.e., they can also overhear. When the SCBSs connect to the core network through a wireline backhaul, the network topology is similar only in this case SCBS B_2 can only overhear a packet transmission from SCBS B_1 and not the MBS. From the previous scenarios, we see that in dense SCNs there will be ample opportunities for collecting information from the neighborhood of each SCBS. In this paper we aim to exploit to the fullest these opportunities that arise from a fundamental property of a wireless channel which is its broadcast nature.

The first central idea of our proposal is to allow SCBSs to passively overhear data packets, so that several nodes have available the same information (packet). This means that the SCBS who has the opportunity to transmit a packet, can do so by selecting from a higher number of candidate packets. The second central idea of this paper is to leverage these overheard packets that are available in the multiple SCBSs in order to obtain a diversity gain for the transmitted signals, but in a way that is aware of the video content of the packet that will be transmitted.

The previous ideas are implemented with two protocols/algorithms. Our concrete contributions that build incrementally one on top the other are:

1. We propose a lightweight packet overhearing protocol for *dense SCNs* that operates between the SCBSs and is based on the concept of opportunistic communication. The cooperative protocol allows the SCBSs to overhear packets and ensures that duplicate video packet forwarding from different SCBSs is avoided.

2. After the previous protocol is applied and ensures that no duplicate packets are forwarded, our second contribution is an algorithm for video-aware optimized relay selection. Video-awareness is embedded in the relay selection process through a new utility metric that combines the importance of the video packet and the achievable data rate of a particular relay.

Our techniques are *fully distributed* and require 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.

2 Related Work

Network cooperation for wireless video distribution has been investigated thoroughly. 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 wireless transmitted video. State-of-art wireless cooperative techniques at the network layer combine algebraic network coding and video transmission [5, 6, 7]. In these works the authors employ linear NC for mixing video packets before transmission to a multicast group of users. However, one assumption of wireless NC 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 buffer maps (detailed information about precisely what packets they have) for ensuring decodability of the selected code and this has to take place between the destination nodes and intermediate relays [5]. Furthermore, NC is suitable for multicast delivery for maximizing the throughput gains, but in the setup that we adopt in this paper we do not consider multicast transmission. Due to the small-cell nature of the system configuration, the relays in Fig. 1 will be able to reach a small number of users/destinations that are located in their neighborhood and are unlikely to desire the same video flow. Therefore, SCBSs 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 user/destination [3]. In [8] the authors considered video distribution in small cells but for the multicast case where all the users desired the same content. This is a possible scenario but the most prevalent case is the unicast streaming for each user that we focus in this paper [2].

Wireless cooperative transmission of video flows has been studied in the context of the lower 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 [9]. DSTC was 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 DSTC is that the relays must transmit simultaneously which means perfect synchronization is required. Also the authors of that work considered the transmission of a single video flow through multicast, but did not consider multi-user video transmission. When multiple users receive different data from the same source with DSTC, one must also decide about the course of action that each relay should follow for each packet (discard, retransmit etc) [9]. Furthermore, the signal diversity benefits of DSTC can also be achieved in a distributed network with simpler protocols according to which it is enough to select the relay with the best channel [10]. 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 [11] the authors proposed relay selection in a cooperative system by modeling the system as an Markov decision process (MDP). The communication model considers both uplink and downlink cooperative transmissions towards an access point (AP). Even though the approach minimizes information exchange between network nodes, still there is a need for message passing rounds between the relays and the AP.

Finally, regarding works that target video distribution in SCNs caching has been the main approach. Femtocaching was proposed in [8] where the small cells use the typically cheap storage space for content caching. More recently it has also been shown that there is a delicate tradeoff involved between caching and resource use decisions when the backhaul cost is considered [12]. The previous work also investigated the delivery of scalable video that allows more flexibility in the caching decisions. Nevertheless, caching is a method complimentary to our work.

In this paper our main proposal is significantly different from the previous works. The first difference is that we remove the assumption that the source requires the recruitment of relays with a type of request-to-send and clear-to-send (RTS/CTS) exchange like the schemes reported in [10, 11]. The source in our proposal is agnostic to the small cell relays and how they select to cooperate. Furthermore, in small cells the destination nodes cannot send feedback to the source due to the low power operation. The second key difference is that we consider the multiuser aspect and the efficient management of overheard/decoded packets [9]. The third and final difference is that we consider video-awareness into the relay selection process.

3 System Model and Assumptions

Small-Cell Wireless Relay Network Model: In this paper we consider the downlink unicast streaming of a set $\mathcal{N} \triangleq \{1, 2, .., n, .., N\}$ of N pre-compressed and packetized video flows from a single source node (the MBS), to N destination nodes that each one is interested in a specific video flow. Besides the MBS and the destinations, the network also includes M SCBSs that are not the consumers of the video flows but their task is to aid by forwarding traffic to the destinations as seen in Fig. 1. The main concept we propose can be applied to an uplink transmission scenario as well. In that case the source of the video flow is one of the users, and the multiple SCBSs/relays help the user in order to transmit the data to the MBS. Our model allows $M > N$, e.g. if we try to transmit one video flow but there are more than one SCBSs in the neighborhood, then they can help even if they do not currently transmit video to one of their associated users.[2] Now if $M < N$ then we have fewer SCBSs and many flows for which the packets that are received are simply enqueued at the buffers of the fewer SCBSs. In the first version of our network model the backhaul link from the MBS to the SCBS is a wireless link [13]. This means that all the SCBSs can overhear the transmissions from the MBS. In the second version of our network model the backhaul link from the MBS to the SCBS is a wireline link. In this case wireless transmissions occur only from the SCBSs. Thus, SCBSs can overhear only neighboring SCBSs and no transmissions from the MBS.

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 allocation in order to allocate to each flow n the optimal rate r_n given the end-to-end available data rate [14]. For this purpose we use the network utility maximization (NUM) framework [15]. To accomplish that, the packet error rate (PER) 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 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 SCBSs know that they must transmit all the packets in their FIFO buffer (this behavior is similar to employing TCP). However, the packets do not need to arrive in order at the final destination since users employ a playback buffer that reorders the packets. Our approach for estimating the end-to-end rate, and adapting each stream to match this rate, ensures that we avoid playback buffer underrun problems at the destination.

Video Content Model: We consider pre-compressed video, where each video unit is contained in a single packet that corresponds to a single video frame. Furthermore, the rate-distortion (R-D) information

[2]To identify the number of M, i.e. how many SCBSs can help a specific destination, the destination can overhear the periodic advertisements from neighboring SCBSs.

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 $\Delta D(i)$ [16]. In practice, $\Delta D(i)$ is the total increase in the mean square error (MSE) distortion that will affect the video flow if the packet is not delivered to the user by its prescribed deadline [17]. 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.[3] In this way the utility formulation considers also the possible drift that might occur due to the loss of particular packets/video frames.

Utility Function: Different utility functions can be employed by the video server that executes NUM. In our case, the utility function is defined as the reduction of the reconstruction distortion of a specific video flow:

$$u(r) = \sum_i \Delta D(i) \quad \text{with} \quad \sum_i \Delta R(i) \leq r. \tag{1}$$

Now, in order to compute the utility $u(r)$ in (1) we previously label the media packets comprising the presentation in terms of importance using the procedure from [18]. Therefore, the index i in the summations in (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. Also in this utility function one could also incorporate the impact of packet deadlines as in [19, 20, 21].

Channel Access: The channel access scheme employed by the source node and the relays follows a simple structure widely adopted in cooperative networks. The basic cooperative protocol separates a single time slot into two phases (see Fig. 2). The source node broadcasts in the first phase. During this first phase the M relays also overhear this transmission but do not acknowledge it since it is broadcast. 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 paper. After the transmission the destination acknowledges this transmission. The acknowledgment is necessary in the second hop of the communication model since there is a need to estimate the channel gain.

Channel Model and PHY Modulation: At the PHY we 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 source s 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.

MCS & CSI: A modulation and coding scheme (MCS) with m bits/symbol is used by the MBS and the SCBSs while its optimal value is determined by each node independently. The set of available MCSs is $\mathcal{C} = \{1, ..., 6\}$, i.e. we assume that the most spectral efficient MCS is 64-QAM and as the IEEE 802.11a standard. Details for the used MCS model can be found in [22]. We also assume that users provide only *average channel quality* feedback (CQI) to the base stations.

Implementation Requirements: Regarding the proposed system we have defined a set of strict requirements motivated by current cellular standards that make use of the SCN architecture. 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 users/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 SCBSs (e.g. application-layer transcoding) besides a decision regarding their forwarding or discarding. Thus, the SCBSs do not collect information pertinent to the used algorithm by using a specialized protocol or message passing. We believe that this is an important design choice since it can be incrementally 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 [8].

[3] For example the ΔD for an I frame includes the ΔD of the P and B frames that depend on it.

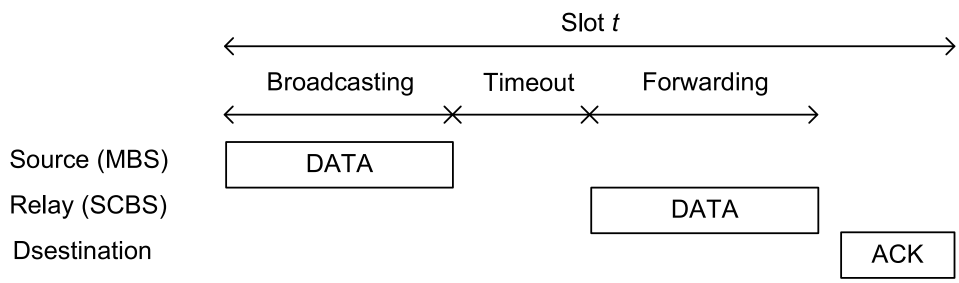


Figure 2: Behavior of the cooperative protocol in the time domain.

Stream Adaptation at the Source: As we explained in our system model, in the proposed system each destination/user periodically forwards 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 complete end-to-end system, and broadcasts (in case of a wireless backhaul) the optimal packets according to the NUM algorithm. Now, as shown in [18] 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 $\Delta D(i_n)/\Delta R(i_n) > \lambda^*$, where λ is the Lagrange multiplier from the NUM.

4 SCBS Overhearing Protocol

In this paper our goal is to fully exploit the broadcast property of the wireless channel around the SCBSs which means that we must practically exploit the fact that many SCBSs may receive the same packet. But how do we ensure that duplicate packets are not forwarded from the relays? The first significant component of the proposed system is the overhearing protocol that is responsible for this task. Fig. 3 depicts an example where the contents of the receive buffers at each SCBS are shown. Depending on the backhaul link setup, and because of the randomness of the wireless channel different broadcasted packets will be received at different SCBSs. When a SCBS forwards a packet to the next hop destination, the remaining SCBSs may also overhear this transmission and its acknowledgment. In this example the first transmitted and overheard packet is p_1.

A pseudo-code for the SCN video packet overhearing (VPO) algorithm is presented in Fig. 4. The notation we adopt follows the IEEE 802.11 frame formats since this protocol is practically possible to be used for a testbed implementation. In our implementation the SCBSs employ a type of pseudo-broadcast by transmitting with unicast to their respective next hop and allow overhearing. The SCBS at the application layer uses the process *tx_pkt_app*() in order to enqueue to the MAC layer packets that are overheard (buffer **OBF**), and also packets that are directly arriving at the SCBS from the wireless or wireline backhaul (buffer **BF**). When the SCBS is granted access to the channel the MAC layer transmits without any further interaction with our algorithm the head-of-line (HOL) packet. An important part of the functionality occurs in the procedure *rcv_pkt_app*() that receives packets from the operating system (MAC and network layers). In this case we require that the MAC layer passes all the information from the MAC protocol data unit (MPDU) to the application.[4] The VPO algorithm checks if the MPDU corresponds to a data packet and in this case it places it in the **OBF** buffer. It also stores the MPDU sequence number in order to keep track of the transmission of this specific MPDU (loss or success) as we describe next. When the MPDU that is delivered to the application is an ACK, then the algorithm checks if this ACK acknowledges an MPDU that is stored in the **OBF** buffer. If this is the case, it removes it since the interested destination has received it. By following this approach, the neighboring SCBSs know that in the case they also have an overheard packet in their buffer, there is no need to transmit it

[4] This is possible in Linux through the socket buffer (`sk_buff`) data structure.

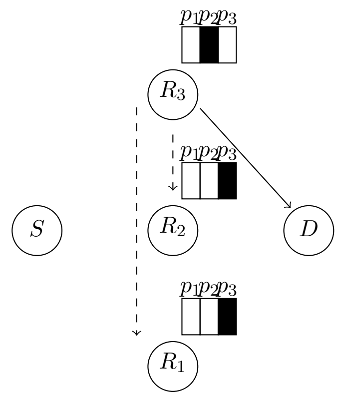


Figure 3: Example of the overhearing algorithm operation when three packets (p_1, p_2, p_3) have been transmitted through a wireless backhaul. Dark-shaded blocks indicate packets that are not available at a particular relay because they were lost during transmission from the source or MBS. Dashed lines denote overhearing.

when they obtain the channel. In case a packet transmission fails this is detected by the lack of an ACK and all the SCBSs retain the lost packet in the **OBF** buffer since any one of them may transmit in the next opportunity. *In summary, the protocol ensures that the SCBSs know which SCBS transmitted what packet and what was the outcome (but not the precise contents of the buffer of each SCBS like network coding-based algorithms).* Therefore, the overhearing protocol allows the SCBSs to forward uniquely each packet to a user.

5 Distributed Video-Aware Relay Selection

Now the relays have a number of available overheard packets, and are also in a position with VPO to know which packets have been transmitted and what was the outcome. *So the VPO protocol essentially limits the options for a relay to only the packets that will be useful for a destination. But from all the candidate packets how to select which one to transmit?* 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 [23]. 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 [10]. In this paper cooperative diversity is also employed. *The novelty is that our system identifies not only 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 or a SCBS/relay, 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.*

5.1 Problem Formulation

The last observation that motivates this second part of this paper 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 Shannon capacity $W \log(1 + \frac{P|h|^2}{N_0})$ can be seen as the number of bits/sec that the channel can reliably transmit [23]. Our description of the

```
tx_pkt_app()
if OBF!=NULL then
    p=OBF→ HOL
    tx_pkt_mac(p,p→ dst)
else
    p=BF→ HOL
    tx_pkt_mac(p,p→ dst)
end if
rcv_pkt_app()
p=rcv_pkt_mac() //Block here waiting for pkt from MAC
if p→ MPDU→ type==DATA then
    if p→ MPDU→ dst==D then
        add(p,OBF,p→ MPDU→ SeqNo)
    end if
    if p→ MPDU→ dst==thisnode then
        add(p,BF,p→ MPDU→ SeqNo)
    end if
else if p→ MPDU→ type==ACK then
    if p→ MPDU → Addr1==D then
        remove(p → MPDU→ SeqNo,BF) OR
        remove(p → MPDU→ SeqNo,OBF)
    end if
end if
```

Figure 4: Pseudo-code for overhearing protocol at a SCBS.

optimization problem further clarifies the practical use of the previous observation. Let us denote the utility and the length of the current head-of-line (HOL) packet at relay r as ΔD_r and ΔR_r respectively.[5] 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 selected in the current slot. Thus, the problem of *video-aware relay selection (VARS)* over a narrowband fading channel is defined as follows:

$$\max_{\vec{x}} \sum_{r=1}^{M} x_r \frac{\Delta D_r}{\Delta R_r} \log\left(1+\frac{P|h_{r,d}|^2}{N_0}\right)$$

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

$$\sum_{r=1}^{M} x_r = 1 \text{ (C2)}$$

The rationale of this form of the optimization objective is that the utility of the HOL 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 $\frac{\Delta D_r}{\Delta R_r}$ of a specific packet, with the instantaneous achievable rate of the Rayleigh slow fading channel.

Example 1 *Consider two relays with* $|h_{1,d}|^2 = 0.5 < |h_{2,d}|^2 = 1$. *Assuming* N_0=10^{-6} *W/Hz,* P=*10mW,* W=*20MHz, and an optimal capacity-achieving AWGN code, relay 1 can reliably communicate at a rate* $\log\left(1+\frac{P|h_{1,d}|^2}{N_0}\right) \approx 0.32$ *bits/Hz, while the second relay at 0.58 bits/Hz. In our tested sequences, a typical value for* $\Delta D/\Delta R$ *for an I frame is arround 1000 and for P frames the utility values start from arround*

[5] Note that this is irrespective of the destination of the packet.

1000 and it reaches a value around 100 for the frames located at the end of the GOP. Even if the second relay can reliably communicate more bits, we can clearly see that the result is that if a packet of high utility like an I frame is available at the first relay this specific packet is selected for transmission.

When a packet to be transmitted has size ΔR that is larger than the achievable channel rate, then we cannot reliable communicate this number of bits within T_{slot} seconds. This is captured by the first constraint (C1) of the problem formulation. When this constraint is not satisfied this is usually referred to as an outage event. Constraint C2 ensures that only one relay transmits.

5.2 Distributed Solution with Video-Aware Channel Access and Relay Selection

Now the first question is how to solve the video-aware relay selection problem, formulated as a linear program (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 $h_{r,d}$. Furthermore, since the channel fade $h_{r,d}$ may change randomly on a packet-basis, we cannot afford communication between the relays. Thus a distributed solution is necessary. 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 [10, 24].

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 [23]. To solve the problem 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 the timer is set equal to:

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

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. Note that the duration of the timer is very small relative to the packet duration (a few PHY symbols compared to a few thousand symbols) and that is why we ignore its duration later in our evaluation. Still, this approach may lead to a collision as it is the case will any randomized channel access scheme. However, the collision probability depends heavily on the number of nodes which in our case is not significant since they are only relays. *This is second novel aspect of our relay system: The optimal small cell relay is not the one that simply has the best channel h, but the one that has the most important HOL media packet and it can also transmit it reliably without the channel being in outage.*

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, 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 maximum PHY communication rate is equal to 802.11a, i.e., 54 Mbps. Packet size of 1500 bytes is used. This means that the time duration of a packet is equal to 54Mbps/1500bytes=22msec. This also makes the duration of a time slot equal to 44msec. The average channel SNR depicted in the horizontal axis of all the figures is assumed to be the same for all the links but it varies independently during each channel realization. We also test the ARQ mechanism for the evaluation of the above systems. These ARQ feedback messages are assumed without error. Note that in all figures we present the utility divided by the number of required time slots for delivering a prescribed media file. This means the impact of ARQ delay is also considered.

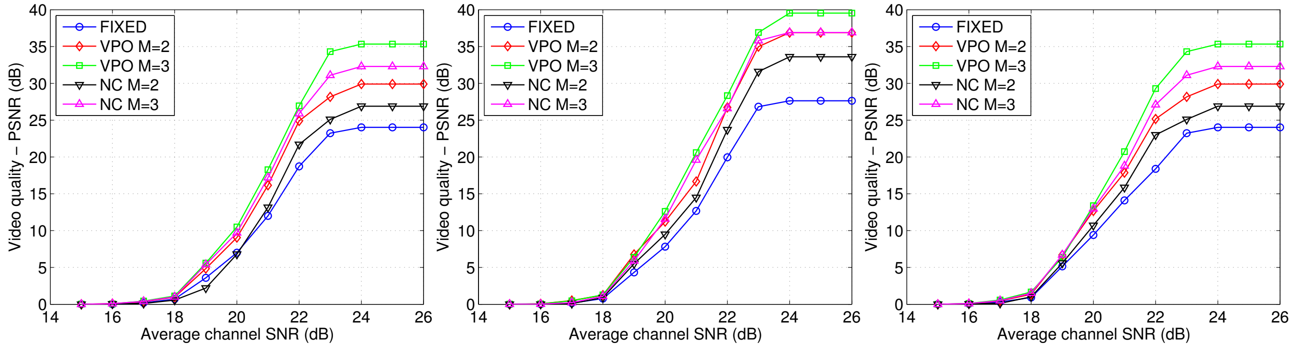
The rate allocation at the source is exercised for the duration of 10 GOPs. The media content used in the experiments consists of the CIF sequences, MOTHER & DAUGHTER and FOREMAN that were compressed using the H.264 codec [25] at a very high rate of less than 8 Mbps. The average peak signal-to-noise ratio (PSNR) for these sequences is 46 dB. The reason we compressed the sequences at this high rate is that the simulated 54Mbps PHY allows for very fast data transmission. Each video frame corresponds to one slice and each slice was packetized to a single packet. For the experiments with two video flows both sequences are used. A number of 300 frames from 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 is set to 32 frames. Also, the startup/playback delay of the video presentation at every node is equal to 5 seconds. In all the figures, the results correspond to the average PSNR enjoyed by all the destinations for the duration of 300 seconds (the same 300 frames were repeatedly transmitted). Finally, we must mention that we do not use any form of error concealment in order to demonstrate clearly the impact of our specific metric/optimization scheme.

6.1 Performance Evaluation of the Overhearing Protocol

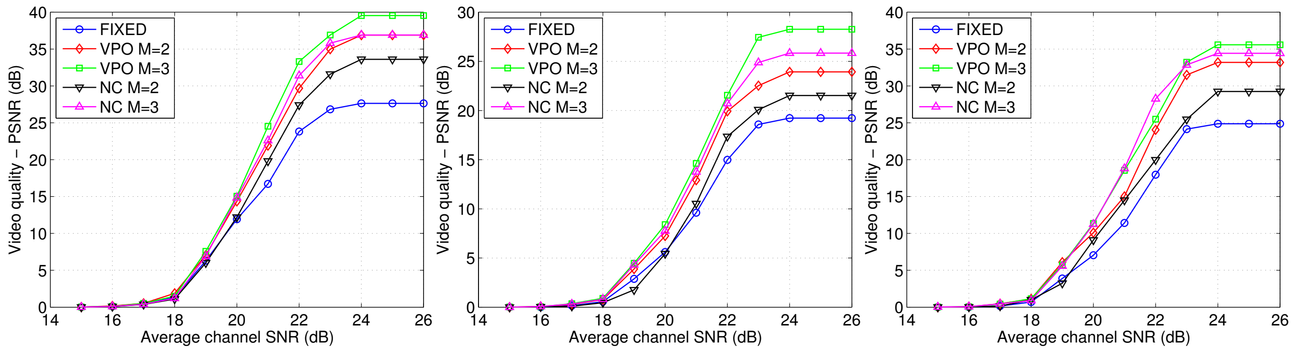
For the first part of the simulation we examine the performance of VPO. We compare against different algorithms that determine how the network treats packets. The system named FIXED uses one specific SCBS for each user and it is the baseline system. We also implemented opportunistic NC of the MORE scheme [7], that moves one step further and encodes packets at the SCBSs. For the NC scheme we limit the feedback messages between the nodes to be at most 5% of the total bandwidth used. Note that here both VPO and NC do not use any relay selection algorithm. Instead, the SCBS relay that will transmit a packet is selected randomly. This is possible because VPO ensures that the SCBSs contain only useful packets in their buffers. For the NC case details about this method can be found in [26]. The previous packet processing algorithms were tested both for a system that did not employ rate allocation at the source namely noNUM, and a system that employed the NUM step at the streaming server and is denoted as NUM in the figures. For the experiments with one video flow the sequence MOTHER & DAUGHTER was tested while both of them were used in the two-flow experiment.

Simulation Results for Wireless Backhaul. Results for streaming one video flow are shown for the noNUM system in Fig. 5(a), while results for the NUM system are shown in Fig. 5(b). The increased number of SCBSs results in higher capacity and eventually higher video quality because a single packet that is broadcasted from the MBS has higher probability to be received at a group of SCBSs instead of just one. We notice that for the NUM system the rate of increase of the average utility is higher as the channel quality is improved when compared with the case of noNUM. The reason is that when the channel is poor, then more critical video packets are not delivered to the user while the opposite happens when the channel is good. This result clarifies the first main point we want to come across from this paper. That is, the proposed streaming framework is more important to be used in the small cell when the channel is good and not so much when the channel is bad. The reason is that for good channel conditions the channel capacity is higher when more relays are used. Another interesting behavior, that we can see in most figures, is that as the channel SNR is increased, the quality for all schemes becomes a flat line. This behavior is well known and is because of the use of the highest possible MCS [22].

We also evaluated a system where we enabled the ARQ mechanism that typically exists at the link layer (IEEE 802.11, LTE). The related results can be seen in Fig. 5(c,d). We see now that ARQ is used, the performance of the systems is only affected in the low SNR regime where significant packet loss is observed. For example for the noNUM systems and for a chanel transmit SNR of 21dB, the ARQ system achieves a video quality PSNR of 21dB, while the system with no ARQ in Fig. 5(a) a PSNR of 18dB. Still, this improvement is not significant in terms of the viewing experience. The NUM system reaches a higher PSNR of 25dB. Hence, ARQ on its own does not lead to improvements but it has to be combined with NUM for all systems. VPO is able to capitalize on this combination even more than any other system.



(a) One flow - No ARQ - noNUM (b) One flow - No ARQ - NUM (c) One flow - ARQ - noNUM



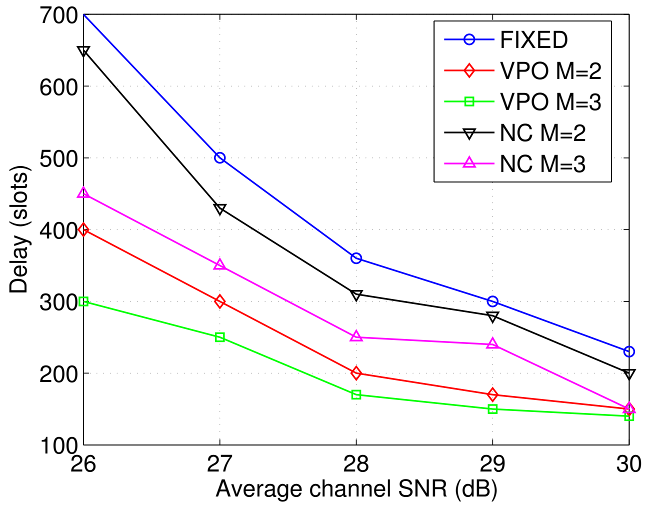
(d) One flow - ARQ - NUM (e) TWO flows - No ARQ - noNUM (f) TWO flows - No ARQ - NUM

Figure 5: Average video quality,i.e., PNSR in dB, vs. the channel transmit SNR in dB.

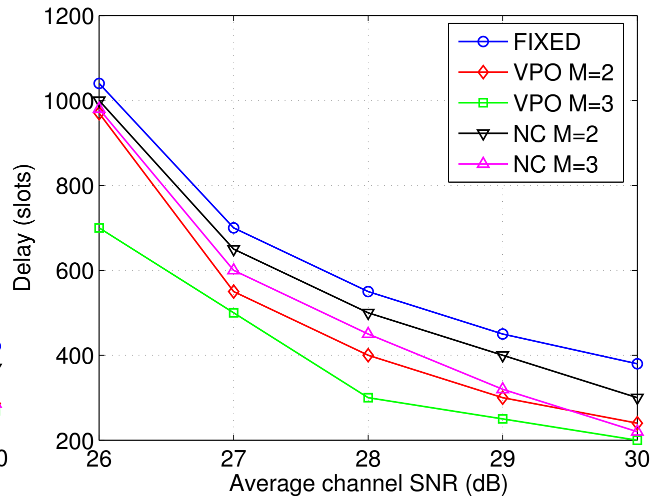
Simulation results for the wireless backhaul case and two video flows can be seen in Fig. 5(e,f). As it can be seen also in this figures, the results have the same form as the results for one flow. As the channel quality is improved and the number of SCBSs is increased, the NUM system presents higher gains when compared to the noNUM system. Results for the ARQ case, that are not presented, lead to performance improvement in the moderate channel SNR regime (19-22dB) similarly with before.

Comparison with Network Coding. NC offers benefits for relatively high SNR. However, in this case the majority of wireless packets are received by all the SCBSs and so there is no NC benefit when compared to our proposed scheme. On the other hand, in the low SNR regime the benefit of NC is similarly limited with VPO because the packet coding opportunities are less due to the high packet loss. This situation is true also for all the NUM systems as it can be seen for example in Fig 5(e) 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 SCBSs exist and the flows are unicast.

Delay Results with Wired Backhaul. Results for the end-to-end delay of the system without NUM can be seen in Fig. 6. These results correspond to the delivery delay for a fraction of the video flow equal to 10 seconds of playbable video. When the backhaul is wired, the capacity cannot be increased since it is limited by the point-to-point backhaul connection. Our measurements in this case show that the benefit of VPO with more than one SCBS is because of the lower packet error rate for individual packets and the reduced need for re-transmissions. When a packet is lost from the primary SCBS this incurs an additional delay for its delivery with NC since these systems typically employ a backoff algorithm [5, 26]. *With VPO this delay is minimized because the lost packet from a SCBS is retransmitted from its neighbor and there it resides at the head of the queue.* This is a key benefit of our proposed system in SCNs that deploy a wired backhaul. Even when no re-transmissions are allowed from a SCBS, VPO still performs better since the remaining SCBSs can all transmit at least once each packet.



(a) No ARQ - noNUM



(b) ARQ - noNUM

Figure 6: Total delay vs. the channel transmit SNR for a system without optimization (noNUM).

6.2 Performance Evaluation for SCBS Selection

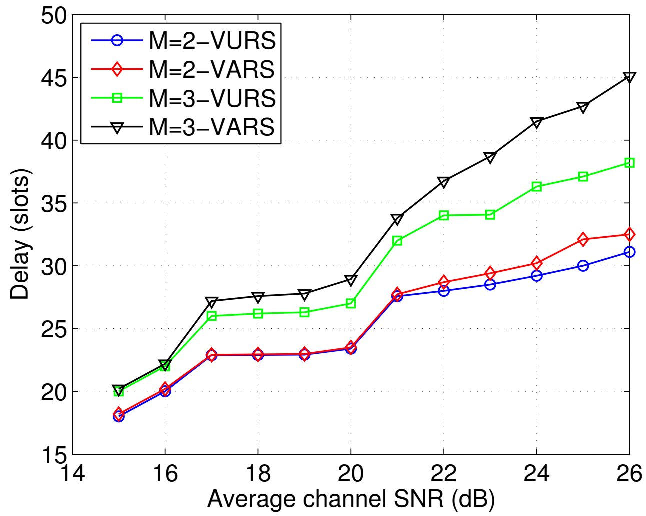
In the second part of our evaluation we examine the performance of video-aware relay selection (VARS). We compare against an algorithm named video unaware relay selection (VURS) and uses a relay selection scheme that takes into account only the best channel $h_{r,d}$ between the relays and the destination [10]. Note that this scheme is what is typically proposed for ensuring the maximum diversity gain in a cooperative relay system. Both relay selection schemes operate on top of te VPO protocol to ensure fairness. Also, NUM is used in all the evaluated systems now.

In this section, we study the video quality that can be achieved with all the systems we described before. Results for streaming to two destinations the two video flows can be seen in Fig. 7(a). For lower values of the average channel SNR the relay selection schemes show almost the same behavior. This is because in the low 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 VURS. This means that when the channel quality is good, the utility of the video packet is a crucial factor for the optimal 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 in Fig. 7(b). We see now that ARQ has impact on the quality of the both systems in the low channel SNR regime.

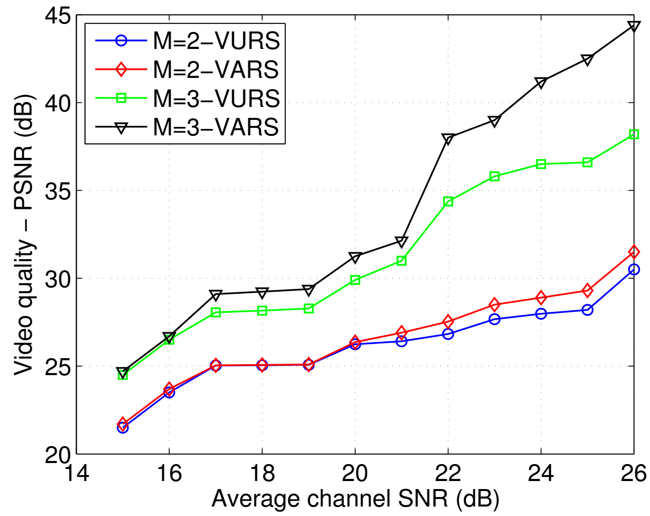
Another key benefit of our approach is that it takes into account the precise utility of each video packet. In Fig. 7(c,d) we present the average quality for each one of the destination nodes for the first of the previous experiments, i.e., without the use of ARQ. As it can be seen in this figure, we 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. However, even sequences with low motion will obtain a fraction of the resources because the most important packets even for these sequences have high utility (e.g. I frames).

7 Conclusions

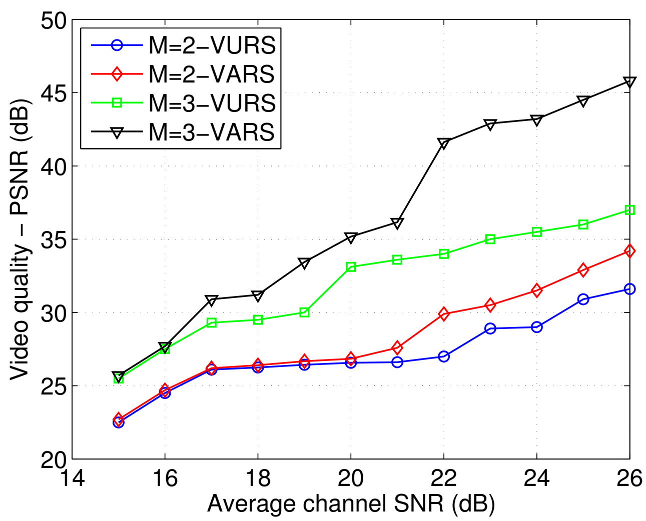
In this paper we presented a framework for video streaming in dense small-cell wireless networks. Our first contribution was the design of a packet overhearing protocol that exploits the natural diversity that this emerging network paradigm offers. For this system we demonstrated that it is enough to allow overhearing



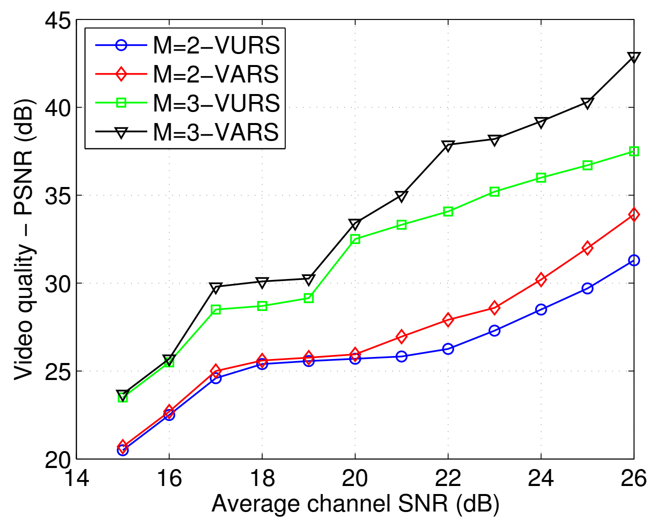
(a) Average video quality of the two flows MOTHER & DAUGTHER and FOREMAN. No ARQ



(b) Average video quality of the two flows MOTHER & DAUGTHER and FOREMAN. ARQ



(c) Video quality for FOREMAN. No ARQ



(d) Video quality for MOTHER & DAUGHTER. No ARQ

Figure 7: Video quality results for the relay selection algorithms.

of video packets and employ our distortion optimized streaming approach instead of employing more sophisticated network coding techniques. Interestingly, our overhearing protocol offers different benefits depending on the SCN backhaul configuration. Our evaluation indicated that in the wireline backhaul case video delivery is accelerated because packet losses from the primary SCBS incur lower link-layer delays. In the wireless backhaul case our system improved the available capacity for video communication.

Our second contribution was a video-aware relay selection algorithm for flat fading channels. Our motivating observation was that even though the broadcast nature of the wireless channel and overhearing allow the same packet to be available at many relays, this does not mean that the relay that has the best channel towards the destination has also received an important video packet. Our relay selection algorithm used a new metric that couples the importance of a video packet with the relay selection process. The performance results showed the significant performance benefits of the combined overhearing protocol and relay selection algorithm in this case.

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