Joint Optimization of HD Video Coding Rates and Unicast Flow Control for IEEE 802.11ad Relaying

Joongheon Kim, *Member, IEEE,* Yafei Tian, *Member, IEEE,* Andreas F. Molisch, *Fellow, IEEE,* and Stefan Mangold

***Abstract*—This paper proposes a joint optimization framework for minimizing high-definition (HD) video coding rates and selecting optimal relay nodes in 60 GHz millimeter-wave (mmWave) IEEE 802.11ad very high throughput (VHT) wireless systems. While IEEE 802.11ad VHT aims to support uncompressed HD video wireless transmission, its major limitation is the extremely high attenuation even in line-of-sight situations, which leads to a short admissible distance between transmitter and receivers and/or the necessity to compress video. To deal with this problem, the IEEE 802.11ad VHT draft standard defines efficient relaying protocols to extend the network coverage. When multiple source-destination pairs and multiple relays are present, a key question is which relay should help in the forwarding of which source flow. This selection should be done in such a way that the average video quality of the streams, which is related to the throughput in a *nonlinear* way, is maximized. We solve this problem by an integer programming framework that selects optimal relay nodes, their cooperation modes (i.e., amplify-and-forward, decode-and-forward, or non-cooperation), and the video coding (compression) rates which can maximize transmission quality.**

***Index Terms*—60 GHz mmWave, IEEE 802.11ad VHT, Relaying, Uncompressed HD Video Transmission, Integer Programming, Cooperative Communications**

I. Introduction

In recent years, data transmission in the millimeter-wave (mmWave) range has received significant attention by the wireless communications and consumer electronics communities. In particular the 60 GHz frequency range is of great interest: a 7GHz wide band (58-65 GHz) has been made available for unlicensed operation. This large bandwidth enables multi-Gigabit/s wireless transmission [1][2], which enables, in turn, video transmission with little or no compression. Therefore, several industry consortia such as WirelessHD [3] and Wireless Gigabit Alliance (WiGig) [4] have been developing related standards. Also within the IEEE, there are two 60 GHz mmWave standardization activities, namely the IEEE 802.15.3c Millimeter Wave Alternative PHY [5] (completed in 2009) and the IEEE 802.11ad Very High Throughput (VHT) [6] (draft 2.0 was released on April 2011).

J. Kim is with the Department of Computer Science, University of Southern California, Los Angeles, CA 90089, USA e-mail: joonghek@usc.edu.

Y. Tian is with the School of Electronics and Information Engineering, Beihang University, Beijing 100191, China e-mail: ytian@buaa.edu.cn.

A.F. Molisch is with the Ming Hsieh Department of Electrical Engineering, University of Southern California, Los Angeles, CA 90089, USA e-mail: molisch@usc.edu.

S. Mangold is with Disney Research, Zurich, Switzerland e-mail: stefan.mangold@ieee.org.

A.F. Molisch is a corresponding author.

The main challenge for 60 GHz transmission is the short transmission range due to the high pathloss, which is inherent in the high carrier frequency. One promising way to deal with this problem is using relays to extend the coverage [7][8].

The main objective of this paper is to design a relay selection framework that can maximize the total achievable rates in 60 GHz video transmission systems; we use IEEE 802.11ad VHT systems as a representative example, since it supports relaying as part of the standard. Our reference network model has multiple source-destination unicast pairs and we assume that the transmissions of the different video streams do not interfere with each other, due to the high directionality of the antennas in the system. The relays can be operated in amplify-and-forward (AF-CC) or decode-and-forward (DF-CC) cooperative mode. Alternatively, the source-destination pairs can directly communicate with each other without relaying, i.e., in non-cooperative communications (non-CC) mode. If transmission capacity for a flow is insufficient for uncompressed transmission (i.e., lower than 1.5 Gbps), video coding (compression) is used. Our proposed framework can make each unicast pair select its own relay and operating mode to maximize average quality of the video flow and compute the optimal coding rate of each flow.

The remainder of this paper is organized as follows: Section II presents an overview of relaying in the IEEE 802.11ad standard, a review of the related literature, and a description of the reference model. Section III presents the proposed integer programming formulation for joint optimization of HD video coding rates and relay selection. Section IV presents performance evaluation of the proposed scheme and section V concludes this paper and suggests future work directions.

II. Preliminaries

A. Relaying in the 802.11ad Standard

Due to the limited coverage of IEEE 802.11ad VHT, the draft [6] defines two kinds of relaying, i.e., link cooperating (LC) and link switching (LS) [9]. In LS, if the source-destination direct PHY link is disrupted, the source redirects the transmission of frames addressed to the destination via the relay. The direct link between the source and destination can resume after the direct link between them is recovered. In LC a frame transmission from the source to the destination is repeated by the relay even when the source-destination link is used at the same time. It can possibly increase the signal quality received at the destination by taking the advantage of cooperative diversity and improve network capacity significantly [10]. For LC, both AF-CC and DF-CC are possible.

Since it offers better performance than LS, we henceforth only consider LC. Furthermore, the possibility of source and destination communicating with each other without relaying (non-CC) needs to be taken into account.

B. Related Work in the Literature

The literature related to the proposed algorithm covers two areas, namely relaying for multi-hop wireless networks and video transmission over wireless networks. Due to the large number of related papers, we cite only some representative examples.

Concerning relay selection, there are a large number of papers for multi-hop wireless networks. The main research trends are utility-maximum opportunistic routing [11], capacity maximizing relay selection with cooperative diversity [7], utility-maximum relaying selection for various multi-hop wireless systems such as IEEE 802.16j systems [12], wireless mesh networks [13], wireless sensor networks [14][15], and so forth. However, only few consider a scenario that is comparable to ours, where the use of 60 GHz transmission allows the elimination of interference through directional characteristics[1]. As a matter of fact, most papers (e.g., [13]) use the assumption of full interference between links, which is reasonable in the microwave range where the achievable directionality of the links is much lower. Other papers might neglect interference but consider scenarios that otherwise deviate from our assumptions, and which require rather complicated solutions (e.g., [7] considers a multi-flow multi-hop network). Ref. [8] describes the general feature of 60 GHz relaying systems with multiple flows and multiple hops. However, it does not consider cooperative relaying with AF-CC and DF-CC, but rather regular multi-hop relaying only.

For video transmission over wireless networks, most of the research contributions focus on video coding to transmit multimedia data over bandwidth-limited wireless links [18]. Though many video coding schemes are already developed [18][19], uncompressed video transmission is not possible in the widely used 2.4GHz or 5 GHz, yet. In 60 GHz mmWave, this uncompressed video transmission *is* possible [20]. For example, the IEEE 802.11ad standard divides the available bandwidth into 2.16 GHz wide subchannels, each of which is capable of supporting uncompressed HD video transmission. Research is being done for error correction [21], MAC-layer design [20], and hardware implementation [22].

C. A Reference Cooperative Relaying Model

Let us assume that there are three types of nodes: source (s), relay (r), and destination (d). They are connected via wireless links and the topology setting is done in such a way that s can transmit data to its associated d and/or to any r; if r receives data from s, it can forward them to d. Then, there are three scenarios:AF-CC, DF-CC, and non-CC (i.e., r is not used). In AF-CC, the achievable rate ($\mathcal{A}_{\text{AF}}$) when using r between s and d is [10]:

$$\mathcal{A}_{\text{AF}} = BW \cdot \log_2\left(1+\text{SNR}_{sd}+\frac{\text{SNR}_{sr}\cdot\text{SNR}_{rd}}{\text{SNR}_{sr}+\text{SNR}_{rd}+1}\right) \quad (1)$$

where $\text{SNR}_{sd} = \frac{P_s}{\sigma_d^2}|h_{sd}|^2$, $\text{SNR}_{sr} = \frac{P_s}{\sigma_r^2}|h_{sr}|^2$, $\text{SNR}_{rd} = \frac{P_r}{\sigma_d^2}|h_{rd}|^2$, and BW means the available bandwidth of a 60 GHz mmWave channel, i.e., 2.16 GHz. h_{sd}, h_{sr}, h_{rd} is the (amplitude) channel gain, including the effects of path-loss, shadowing, and small-scale fading between s and d, s and r, r and d, respectively. In addition, z_d and z_r are the zero-mean additive white Gaussian noise at d and r with variance σ_d^2 and σ_r^2. P_s and P_r are the transmit powers at s and r. In DF-CC, the achievable rate ($\mathcal{A}_{\text{DF}}$) when using r between s and d is [10]:

$$\mathcal{A}_{\text{DF}} = BW \cdot \min\{\log_2(1+\text{SNR}_{sr}), \log_2(1+\text{SNR}_{sd}+\text{SNR}_{rd})\} \quad (2)$$

In non-CC, the achievable rate ($\mathcal{A}_{\text{NC}}$) is [10]:

$$\mathcal{A}_{\text{NC}} = BW \cdot \log_2(1+\text{SNR}_{sd}) \quad (3)$$

Among these three methods, no single method is optimum all the time. Hence, an adaptive cooperative mode selection algorithm is required. Note that in the following we assume that the physical layer of the IEEE 802.11ad can achieve the capacity in AWGN, which obviously is an idealization, but allows for closed-form treatment of the relay optimization.

D. Coding Rate Decision for HD Video Wireless Transmission

If the given unicast pair can achieve a data rate higher than 1.5 Gbps, video coding is not required because uncompressed 1080p HD video transmission is possible. This can be understood as follows: In a 1080p HD video stream, one frame consists of 1080×1920 pixels, each of which is represented by $3 \times 8 = 24$ bits (8 bits RGB). 30 frames of image data is transmitted per second in standard mode [5]. Thus, the required data rate to transmit uncompressed 1080p HD video is around 1.5 Gbps ($1080 \times 1920 \times 24 \times 30$)[2]. IEEE 802.11ad VHT has 4 sub-channels with 2.16 GHz bandwidth for each, thus uncompressed HD video wireless transmission can be achieved in ideal channel conditions. However, compressive HD video coding is required in nonideal channel conditions that limit the achievable data rate to below 1.5 Gbps. Such compressive coding leads to a loss in perceived quality of the video; this is modeled by a penalty function. The formulation of this penalty function is a complicated science by itself and furthermore depends on the particular type of video [19]. We thus use here an approximate formulation based on the following considerations: Previous investigations have shown that there is usually no loss in perceived quality when the compression rate is between 0% and 30%. In addition, if the

[1] [16] shows that the mmWave antennas which have very high directional antenna lead to very low levels of interference even with uncoordinated transmissions. In addition, by using the 60 GHz mmWave Cassegrain antenna which is developed by [17], the corresponding wireless links are extremely narrow, i.e., 1 degree beamwidth. Thus the interference is not considered in the integer programming modeling in this paper.

[2] In enhanced mode the number of frames per second is doubled, and thus 3 Gbit/s data rate is required [20]. To simplify the discussion, this paper will only deal with the standard mode.

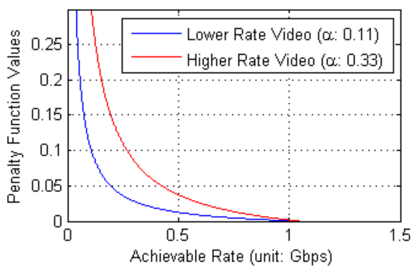

Fig. 1. The penalty function: Red line presents the penalty function which is for the high rate video support. In this case, data loss can be increased comparing to the case of lower rate video support, i.e., the case of blue line. Thus, the curve of red line is more dramatical than the one of blue line.

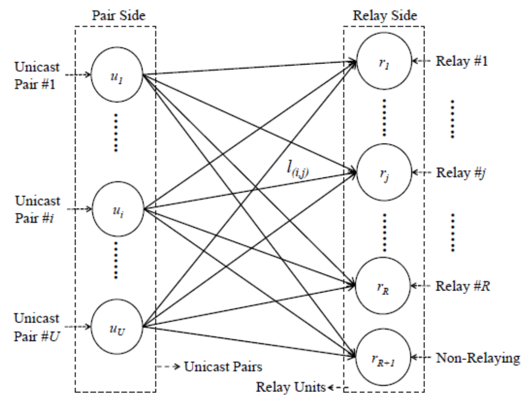

Fig. 2. Logical graph of given unicat pairs and relay units. There are U, R, and $R+1$ numbers of unicast pairs, relay nodes, and relay units.

coding rate becomes around 50%, on average one bit at one pixel is in error. As the compression increases beyond 50%, the corresponding penalty value should increase exponentially according to rate distortion theory. To model this behavior, the penalty function, i.e., $f_{\mathcal{P}}(\mathcal{A})$, is related to the actual data rate, i.e., $\mathcal{A}$, as follows (see also Fig. 1)

$$f_{\mathcal{P}}(\mathcal{A}) \triangleq \frac{\alpha}{24}\left(\frac{k_1 k_2 th_u}{k_1 - k_2}\frac{1}{\mathcal{A}} - \frac{k_2}{k_1 - k_2}\right) \quad (4)$$

where $\mathcal{A}$ is the achievable rate , th_u is the threshold rate for uncompressed wireless HD video transmission, i.e., 1.5 Gbit/s. In addition, k_1 and k_2 are 0.7 and 0.5 to reflect the compression behavior described above. Even though α (scale factor) can be changed by different video sources, accommodating a range of quality perceptions of compressed video, the fundamental behavior of the graph is not changed. The setting of this value plays little role in the relay selection.

III. Problem Formulation

A. Assumptions and Basic Reference Network Models

As mentioned above, one of the key simplifications in our system model is that multiple links (involving t, r, and/or d) can operate simultaneously without mutual interference; this assumption is justified by the high directionality of both antennas and propagation channels at 60 GHz [1]. Using adaptive arrays, transmit and receive antenna elements at the various nodes can form beams that provide good reception of desired signals (possibly simultaneously at relay and destination) while minimizing interference to/from nodes involved in the transmission of other video flows. This fact is helpful for designing a relay selection framework with low complexity [8]. In our reference network model, relays are randomly deployed and at most one relay may interact with each unicast pair. It has been shown in previous work that the performance of multiple relays in parallel is only marginally better than selecting a single (optimal) relay [23]; as a matter of fact under some restrictions on the available channel state information at the transmitter, selection of the single best relay may be optimum [24].

B. Integer Programming Formulation

Based on the above model, a network graph can be established, see Fig. 2. N_u source-destination pairs $u_i, i \in \{1,\cdots,N_u\}$ and N_r relay nodes $r_j, j \in \{1,\cdots,N_r\}$ are present. In addition, one non-CC node, i.e., r_{R+1} in Fig. 2, is present on the relay side, hence each relay can be considered as AF-CC or DF-CC only, because the non-CC mode of all relays is incorporated by the presence of r_{R+1}. According to this basic setting, there are totally N_r+1 (denoted as N_r') number of nodes (henceforth called *relay units*) on the relay side. Each unicast pair has possible links to any relay unit, which can be described by:

$$l_{(i,j)} \triangleq \left(x_{(i,j)}, p_{(i,j)}\right) \quad (5)$$

where $x_{(i,j)}$ is a boolean index for representing the connectivity between u_i and r_j and $p_{(i,j)}$ stands for the penalty function value based on the computed achievable rate of the pair u_i, via relay r_j. For each connection using u_i and r_j, there are two choices for achievable rates, corresponding to AF-CC or DF-CC. $p_{(i,j)}$ takes on the lower of the two associated penalty function values because u_i will choose r_j with the better cooperation mode. The information which cooperation mode is selected is represented by a matrix with Boolean entries

$$\mathbf{M} \triangleq \begin{bmatrix} m_{(1,1)} & \cdots & m_{(1,N_r)} \\ \vdots & \ddots & \vdots \\ m_{(N_u,1)} & \cdots & m_{(N_u,N_r)} \end{bmatrix} \quad (6)$$

where $m_{(i,j)} \in \{\text{AF-CC}, \text{DF-CC}\}$ is defined as

$$m_{(i,j)} \triangleq \begin{cases} \text{AF-CC}, & \text{if } u_i \text{ selects } r_j \text{ with AF-CC.} \\ \text{DF-CC}, & \text{if } u_i \text{ selects } r_j \text{ with DF-CC.} \end{cases} \quad (7)$$

For the integer programming formulation, $p_{(i,j)}$ and $x_{(i,j)}$ are defined as $N_u \times N_r'$ matrices as follows:

$$\mathbf{P} \triangleq \begin{bmatrix} p_{(1,1)} & \cdots & p_{(1,N_r')} \\ \vdots & \ddots & \vdots \\ p_{(N_u,1)} & \cdots & p_{(N_u,N_r')} \end{bmatrix} = \begin{bmatrix} \mathbf{P}_1 \\ \vdots \\ \mathbf{P}_{N_u} \end{bmatrix} \quad (8)$$

where $\mathbf{P}_k$ denotes the k-th row of $\mathbf{P}$, $k \in \{1,\cdots,N_u\}$ and $p_{(i,j)}, j \in \{1,\cdots,N_r'\}$ is the lowest value among $f_{\mathcal{P}}(\mathcal{A}_{\text{AF}})$, and $f_{\mathcal{P}}(\mathcal{A}_{\text{DF}})$.

$$\mathbf{x} \triangleq \begin{bmatrix} x_{(1,1)} & \cdots & x_{(1,N_r')} \\ \vdots & \ddots & \vdots \\ x_{(N_u,1)} & \cdots & x_{(N_u,N_r')} \end{bmatrix} = \begin{bmatrix} \mathbf{x}_1 \\ \vdots \\ \mathbf{x}_{N_u} \end{bmatrix} \quad (9)$$

where $\mathbf{x}_k$ denotes the k-th row of $\mathbf{x}$, $k \in \{1, \cdots, N_u\}$ and $x_{(i,j)}$ denotes the connectivity Boolean values between the i-th unicast pair $u_i, i \in \{1, \cdots, N_u\}$, and j-th relay unit $r_j, j \in \{1, \cdots, N'_r\}$. $x_{(i,j)} \in \{0, 1\}$ is defined as

$$x_{(i,j)} \triangleq \begin{cases} 1, & \text{if } u_i \text{ selects } r_j. \\ 0, & \text{if } u_i \text{ does not select } r_j. \end{cases} \tag{10}$$

Our main objective is *(1) finding the optimal set of* $\mathbf{x}$*, which shows the connectivities between* $u_i, i \in \{1, \cdots, N_u\}$ *and* $r_j, j \in \{1, \cdots, N'_r\}$ *and (2) minimizing the summation of penalty function values for the connected pairs and relay units*. Thus, the objective function can be written as

$$\min \sum_{k=1}^{N_u} \left(\mathbf{P}_k \mathbf{x}_k^T\right) \tag{11}$$

which means the minimization of the summation of penalty values for all unicast pairs. In addition, there are the following two constraints.

1) Constraint #1: Each unicast pair selects exactly one relay unit. Then, for $u_i, i \in \{1, \cdots, N_u\}$,

$$x_{(i,1)} + x_{(i,2)} + \cdots + x_{(i,N'_r)} = 1 \tag{12}$$

which means that $u_i, i \in \{1, \cdots, N_u\}$ is connected to exactly one relay unit (including the "virtual" relay $r_{N'_r}$). Then, the general form of this constraint, i.e., considering all unicast pairs, is $\mathbf{U}\mathbf{x}^T = \mathbf{1}$ where $\mathbf{U}$ and $\mathbf{1}$ are defined as $1 \times N'_r$ and $N_u \times 1$ matrices with elements are 1.

2) Constraint #2: Each relay serves at most one unicast pair. Note that r_{R+1}, i.e., the logical node for presenting non-CC in relay units, is not considered in this constraint because multiple number of unicast pairs can choose non-CC as cooperation mode. Then, for $r_j, j \in \{1, \cdots, N_r\}$,

$$x_{(1,r_r)} + x_{(2,r_r)} + \cdots + x_{(N_u,r_r)} \leq 1 \tag{13}$$

Then, the general form of this constraint, i.e., considering all relays, is as $\mathbf{V}\mathbf{x} \leq \mathbf{1}$ where $\mathbf{V}$ and $\mathbf{1}$ are defined as $1 \times N_u$ and $\mathbf{1}$ matrices and and their elements are 1.

C. Solving the Integer Programming Formulation

In the previous section we derived an integer programming formulation with two sets of constraints. Such problems are generally NP-hard. However, in our case the constraints can be formulated in matrix forms where the matrix elements are 0 or 1. Thus, these are *totally unimodular matrices*, and - as shown in Theorem 1 below - the optimum solution is integer. Hence, the optimal solution can be obtained by general linear programming solving algorithm. Thus, the solution can obviously be obtained in polynomial time.

Theorem 1. *If the constraint matrix M_c in linear programming formulation is totally unimodular, then there exists an optimal solution as an integer [25].*

Proof: If M_c is $m \times n$ where $m < n$, a basic solution is a nonsingular form as an $m \times m$ square submatrix of M_c, i.e., $M_b = (b_{ij})$ and its subset of x_{M_b}. Then, $x_{M_b} = M_b^{-1} b$. by Cramer's rule, it is obious that

$$M_b^{-1} = \frac{M_f^T}{\det(M_b)} \tag{14}$$

where $M_f = (f_{ij})$ is $m \times m$, i.e., the cofactor matrix of M_b. Every f_{ij} is the determinant of a submatrix which is formed by deleting row i and column j from M_b. Then, this is multiplied by an appropriate sign coefficient (i.e., 1 or -1). Thus, by the fact that the determinant is a summation of terms which are the products of entries of the submatrix, all entries in M_f should be integer. Thus, there exists an integer optimal solution. ■

TABLE I
TOPOLOGY SETTING WITH NETWORK SIZE: 100×100 (UNIT: METER)

source (s)	destination (d)	relay (r)
$s_1 = (0.91, 32.11)$	$d_1 = (52.33, 75.03)$	$r_1 = (52.32, 75.01)$
$s_2 = (0.95, 32.07)$	$d_2 = (52.35, 74.99)$	$r_2 = (36.93, 62.12)$
$s_3 = (0.99, 32.03)$	$d_3 = (52.37, 74.95)$	$r_3 = (42.36, 74.92)$
$s_4 = (1.03, 31.99)$	$d_4 = (52.39, 74.91)$	$r_4 = (52.37, 74.88)$
$s_5 = (1.07, 31.95)$	$d_5 = (52.41, 74.87)$	$r_5 = (31.87, 57.71)$
$s_6 = (1.11, 31.91)$	$d_6 = (52.43, 74.83)$	$r_6 = (26.77, 53.37)$
$s_7 = (1.15, 31.87)$	$d_7 = (52.45, 74.79)$	$r_7 = (42.42, 74.77)$
$s_8 = (1.19, 31.83)$	$d_8 = (52.47, 74.75)$	$r_8 = (52.43, 74.73)$

IV. PERFORMANCE EVALUATION

A. Simulation Setting

This section presents simulations of the proposed scheme along with following three comparison scenarios.

- AF-CC-all: Each pair uses AF-CC with the nearest relay.
- DF-CC-all: Each pair uses DF-CC with the nearest relay.
- non-CC-all: Each pair does not use cooperation (non-CC).

where the nearest relay is defined as the relay which has the smallest summation of the distance between relay and source and the distance between relay and destination. We assume a pure line-of-sight scenario without fading, such that the attenuation between two nodes is given by a power-distance law with path loss coefficient (n) is 2.5 [2]. The topology setting is given in Table I. If a relay is the nearest one for multiple pairs, then the relay is used by the pair that can get a higher achievable rate. This simple relay selection scheme ensures that there are no conflicts between flows at relays, and might be considered a "greedy" alternative to our optimized selection method.

B. Simulation Results

This section shows the performance of the proposed framework in terms of the summation of penalty function values (i.e., Fig. 4) and total achievable rates (i.e., Fig. 3). As the number of flows increases, the performance advantage of the proposed algorithm with respect to the comparison scenarios increases - both because it takes optimal cooperation modes for each unicast flow (the lower penalty value corresponds to high performance based on the definition of penalty function.), and a better relay selection methodology. The latter effect is more important in our setting (actually, AF-CC turns out to be the best cooperation mode in this particular example). In the given

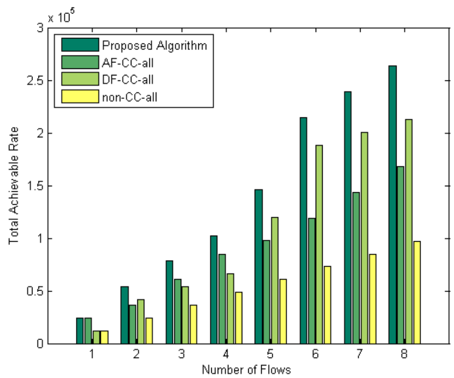

Fig. 3. Total achievable rates ($\text{SNR}_{n_a n_b} = \frac{1}{7}|h_{n_a n_b}|^2$)

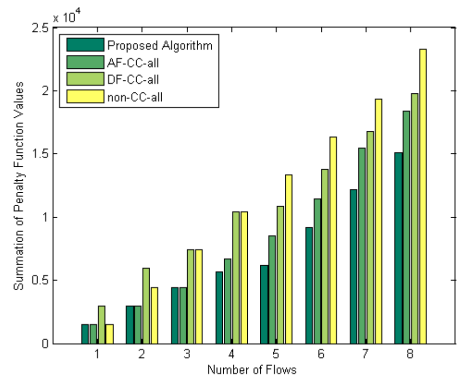

Fig. 4. Penalty function values ($\text{SNR}_{n_a n_b} = \frac{1}{7}|h_{n_a n_b}|^2$, $\alpha = 0.33$)

topology setting, the performance of the proposed algorithm is better than the ones of greedy selection with AF-CC, DF-CC, and non-CC by 21.8%, 30.6%, and 54.0%, respectively.

V. Conclusions and Future Work

This paper proposes a novel optimization framework to select relays that can maximize the total achievable video quality for multiple unicast source-destination pairs in IEEE 802.11ad VHT relaying systems. For this purpose, the proposed scheme formulates an integer programming problem with two constraint matrices that are totally unimodular. Due to the properties of such totally unimodular matrices, the optimal solutions can be computed by general linear programming solving algorithms. The solution is the set of relays and their corresponding cooperation modes, i.e., AF-CC, DF-CC, or non-CC. Simulations verify that the proposed scheme works better than "naive" or "greedy" algorithms, and in particular the use of the penalty function is essential for avoiding situations in which one source-destination pair uses up resources for increasing the admissible data rate beyond the point where it improves video quality.

Probably, joint source-channel coding [26][27] could improve the performance beyond what is described in the current paper, but additional work is required to quantify its impact in our specific settings as a future research direction.

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