# Energy and Content Aware Multi-homing Video Transmission in Heterogeneous Networks

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***Abstract*—This paper studies video transmission using a multi-homing service in a heterogeneous wireless access medium. We propose an energy and content aware video transmission framework that incorporates the energy limitation of mobile terminals (MTs) and the quality-of-service (QoS) requirements of video streaming applications, and employs the available opportunities in a heterogeneous wireless access medium. In the proposed framework, the MT determines the transmission power for the utilized radio interfaces, selectively drops some packets under the battery energy limitation, and assigns the most valuable packets to different radio interfaces in order to minimize the video quality distortion. First, the problem is formulated as MINLP which is known to be NP-hard. Then we employ a piecewise linearization approach and solve the problem using a cutting plane method which reduces the associated complexity from MINLP to a series of MIPs. Finally, for practical implementation in MTs, we approximate the video transmission framework using a two-stage optimization problem. Numerical results demonstrate that the proposed framework exhibits very close performance to the exact problem solution. In addition, the proposed framework, unlike the existing solutions in literature, offers a choice for desirable trade-off between the achieved video quality and the MT operational period per battery charging.**

***Index Terms*—Multi-homing video transmission, video packet scheduling, heterogeneous wireless access medium, precedence-constrained multiple knapsack problem (PC-MKP).**

## I. Introduction

Recently, the wireless communication medium has become a heterogeneous environment with various wireless access options and overlapped coverage from different networks [1]. As a result, mobile users can enjoy a variety of opportunities to enhance their data transmission/reception rates and thus improve the perceived quality-of-service (QoS). Mobile terminals (MTs) are equipped with multiple radio interfaces in order to make use of these available opportunities. One promising service in such a heterogeneous wireless access medium is known as a multi-homing service [2] - [4]. With multi-homing capabilities, MT can utilize all its radio interfaces simultaneously and aggregate the offered resources from different networks so as to support the same application with improved QoS.

Video streaming has gained an increasing popularity among various mobile applications. It has been estimated that, by the end of 2015, more than 65% of all mobile data traffic will come from video streaming [5]. Utilizing multiple radio interfaces of an MT to support video transmission through multi-homing service can improve service quality in many aspects [6], [7]. Sending video packets over multiple networks 1) increases the amount of aggregate bandwidth available to the application, 2) reduces the correlation between consecutive packet losses due to transmission errors or network congestion, and 3) allows for mobility support. It can reduce the probability of an outage when a communication link is lost with the current serving network as the user moves out of its coverage area.

In multi-homing video transmission, packet scheduling should determine which packet should be assigned to which radio interface, given the packet required QoS and the radio interface characteristics in terms of channel condition and available bandwidth. Video packets which missed their playback deadlines should be dropped in order not to waste the network resources. A strategy in packet dropping and assignment to different radio interfaces is to minimize the total video quality distortion. Thus, a video packet scheduling algorithm should be content-aware in order to transmit the most valuable packets and drop the least valuable ones. On the other hand, MT battery energy limitation is a concern in multi-homing video transmission. It has been shown that the gap between the demand for energy and the offered battery capacity is increasing exponentially with time [8]. Hence, the MT operational time in between battery charging has become a significant factor in the user perceived QoS [9]. Besides developing new battery technology with improved capacity, the operational period of an MT between battery chargings can be extended through managing its energy consumption [10]. Thus, packet scheduling should be energy-aware in order to work under the MT battery limitation. However, this concern has been mostly overlooked so far while designing a video streaming packet scheduling algorithm.

Despite the benefits of multi-homing video transmission, employing multiple radio interfaces of the MT results in high energy consumption. How to efficiently exploit the MT multiple radio interfaces to enhance the perceived video quality while satisfying the MT battery energy limitation is addressed in this work. In this paper, we propose an energy and content aware video transmission framework using a multi-homing service in a heterogeneous wireless access medium. The proposed framework takes account of the energy limitation of MTs and the required QoS for video streaming applications, and utilizes the available opportunities in the heterogeneous wireless access medium. Since data transmission over a wireless radio interface consumes a significant fraction of MT energy [10], we focus on an uplink scenario where a mobile user captures live videos on his/her MT and transmits them for posting on social network sites [5]. We summarize the contributions of

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this paper in the following:

- The energy and content aware multi-homing video transmission problem is formulated as a mixed integer nonlinear program (MINLP). The proposed problem formulation captures i) the video packet characteristics in terms of distortion impact, delay deadlines, and packet dependence relation, ii) the characteristics of the multiple wireless interfaces in terms of the channel conditions and the allocated bandwidth, and iii) the MT battery energy limitation. The problem solution determines the power allocation for the radio interfaces, selectively drops some packets given the MT energy constraint, and assigns remaining packets to different radio interfaces with the objective of minimizing video quality distortion;
- Due to the MINLP computational complexity which makes its solution intractable for large number of packets [11], a piecewise linearization approach is employed and the problem is solved using a cutting plane method which reduces the associated complexity from MINLP to a series of mixed integer linear programs (MIPs);
- Solving the MIPs requires that the MT has a commercial optimization solver (such as CPLEX [12]). To avoid the requirement, the video transmission framework is approximated by a two-stage optimization problem that can be easily solved. In the first stage, the allocated power for each radio interface is optimized in order to maximize the achieved data rate given the interface channel condition, available bandwidth, and the MT energy constraint. The second stage solves the packet assignment problem to minimize video quality distortion;
- We show that the multi-homing video packet assignment problem can be expressed as a new variant of the famous knapsack problem [13]. We refer to this new variant as a precedence-constrained multiple knapsack problem (PC-MKP) and propose a greedy algorithm, based on [14], to solve it in a polynomial time complexity of the problem parameters in terms of the number of radio interfaces and the number of packets;
- The performance of the greedy framework is evaluated and compared to the exact problem solution (using the cutting plane method for large-size problems), and two benchmarks (energy independent and content independent video transmission frameworks). Numerical results demonstrate that the proposed greedy framework exhibits performance very close to the exact solution, yet at reduced computational complexity. In addition, the proposed greedy framework offers a desirable trade-off between the achieved video quality and the MT operational period per battery charging, different from the energy independent solutions. Moreover, the proposed framework can achieve the same video quality at reduced energy consumption as compared to the content independent solutions, which is translated to a larger operational period per battery charging for the MT.

The rest of the paper is organized as follows: Section II reviews the related work. Section III presents the video traffic and transmission models. The MINLP formulation of the energy and content aware multi-homing video transmission is developed in Section IV, and the cutting plane method is employed to further reduce the associated computational complexity. The greedy framework is presented in Section V. Numerical results and discussions are presented in Section VI. Finally, conclusions are given in Section VII. Table I summarizes the important mathematical symbols used in the paper.

## II. Related Work

Two categories of video packet scheduling algorithms can be distinguished in the literature. In the first category, video packets are scheduled for single-path transmission, while the second category includes video packet scheduling algorithms for transmission over multiple network paths.

The main objective of single-path video packet scheduling is to schedule packet transmission such that packets do not miss their playback deadlines. Packets whose playback deadlines have passed are dropped so as not to waste network resources. The scheduling policy should incorporate the video packet characteristics (in terms of delay deadline and distortion impact) and the time varying wireless channel condition. In [15], the problem of video packet scheduling is studied for multiple users in the downlink of a wireless communication system. A playout adaptive packet scheduling algorithm is proposed in [16] for video delivery over wireless networks. A cross layer video packet scheduling scheme is presented in [17], which targets downlink transmission. In [18], a Markov decision process is used to formulate the video packet scheduling problem and balance the packet distortion impact with the consumed energy. The energy budget effect is considered in the packet scheduling framework of [19] which aims to maximize the perceived video quality through a joint optimization scheme of modulation and coding, and transmission power allocation. The problem of joint packet scheduling and power allocation is also investigated in [5] in order to minimize video quality distortion for multiple users in the uplink of a code division multiple access (CDMA) network. As the works of [5] and [15] - [19] target single-path video transmission, they do not benefit from the multi-homing video transmission advantages.

Several works in the literature have studied packet scheduling for multi-path video streaming. In [20], a multi-path transmission control scheme is proposed, combining bandwidth aggregation and packet scheduling for real time streaming in a multi-path environment. The streaming policy of [21] consists of a joint selection of the network path and of the video packets to be transmitted along with their sending times. Almost all the multi-path video transmission policies discussed in literature do not target a heterogeneous wireless access medium. Instead, for multi-path video transmission policies in literature, all the used paths belong to the same network such as a mobile ad hoc network. As a result, when energy efficiency is considered, as in [24] and [25], the objective of packet scheduling is to avoid paths along which nodes are suffering from energy depletion. When energy efficiency is

TABLE I
SUMMARY OF IMPORTANT SYMBOLS

| Symbol | Definition |
|---|---|
| $\mathcal{A}_k^f$ | Set of ancestors for packet $k$ of frame $f$ |
| $B_n$ | Allocated bandwidth on the uplink to the MT $n$th radio interface |
| $C_n$ | Transmission capacity of the $n$th radio interface |
| $d_f$ | Delay deadline of a packet that belongs to frame $f$ |
| $E$ | Energy budget per time slot |
| $\mathcal{F}$ | Set of available video frames |
| $\mathcal{G}_n$ | Set of assigned packets to the $n$th radio interface |
| $g_n$ | Channel gain between MT and BS/AP communicating with the $n$th radio interface at a given time slot |
| $h_{kf}$ | Index that gives the radio interface where packet $k_f$ is assigned to |
| $\mathcal{K}_f$ | Set of available packets for video frame $f$ |
| $\mathcal{L}$ | Set of unassigned packets |
| $l_f$ | Length in bits for a packet of frame $f$ |
| $\mathcal{N}$ | Set of utilized radio interfaces |
| $O_n$ | Amount of residual capacity for the $n$th radio interface |
| $P_n$ | Allocated power to the $n$th radio interface |
| $R_n$ | Amount of used capacity for the $n$th radio interface |
| $r(k_f)$ | Required minimum data rate for transmitting packet $k$ of frame $f$ |
| $\mathcal{S}$ | Set of assigned packets to all radio interfaces |
| $v_f$ | Distortion impact of a packet that belongs to frame $f$ |
| $x_{kn}^f$ | Binary decision variable for assignment of packet $k$ of frame $f$ to radio interface $n$ |
| $\tau$ | Time slot duration |
| $\lambda$ | Lagrangian multiplier for the MT energy constraint |
| $\alpha$ | Fixed step size |
| $\eta_0$ | Noise power spectral density |
| $\Delta D$ | Difference in delay deadline for two consecutive frames |

considered in a heterogeneous wireless access medium, one objective is to exploit the available bandwidth and channel conditions experienced by different radio interfaces of an MT in order to support a long duration video transmission with acceptable quality subject to the MT battery energy constraint.

Video streaming in a heterogeneous wireless access medium is studied in [26]. The objective is to investigate the heterogeneous networking attributes that may affect the streaming performance, in terms of the trade-off between jitter frequency and buffer delay. Yet, the work in [26] does not target a multi-homing service and the MT connects only to one wireless access network at a time. The work of [27] studies video transmission in a heterogeneous wireless access medium and employs multi-homing service in downlink transmission. Hence, the works of [5] and [15] - [27] do not investigate how to exploit the channel conditions and available bandwidths at different networks to support uplink multi-homing video transmission while considering the MT battery energy limitation.

In this paper, we aim to develop an energy and content aware framework for multi-homing video transmission in a heterogeneous wireless access medium. The objective is to perform power allocation and packet scheduling to different radio interfaces of an MT, subjected to the MT battery energy limitation, in order to satisfy the packet required QoS in terms of playback deadline and to minimize video quality distortion.

## III. SYSTEM MODEL

### A. Video Traffic Model

A video sequence is encoded into a bit stream using a layered video encoder. The video sequence layered representation consists of a base layer and several enhancement layers [28]. The base layer can be decoded independently of the enhancement layers and provide a basic level of quality. The enhancement layers are decoded based on the base layer and is used to improve the base layer quality. Each video layer is periodically encoded using a group of picture (GoP) structure. Time is partitioned into time slots, $\mathcal{T} = \{1, 2, \ldots, T\}$, of equal duration $\tau$. The total number of time slots, $T$, is based on the estimated video call duration. The MT is assumed to have a new GoP, from every layer, ready for transmission every $\tau$. The data within the same time slot are encoded interdependently using motion estimation, while data belonging to different time slots are encoded independently [18]. Each time slot contains a set $\mathcal{F}$ of frames, from different layers, $\mathcal{F} = \{1, 2, \ldots, F\}$. Each frame can be of I, P, or B type. Frames of I type are compressed versions of raw frames independent of other frames, frames of P type refer to preceding I/P frames, and B frames can refer to both preceding and succeeding frames. Each frame is further encoded into packets and each packet contains data relative to at most one frame [21]. Let frame $f$ be fragmented into $K_f$ packets, $\mathcal{K}_f = \{1, 2, \ldots, K_f\}$, each of length $l_f$ bits. The video packet characteristics can

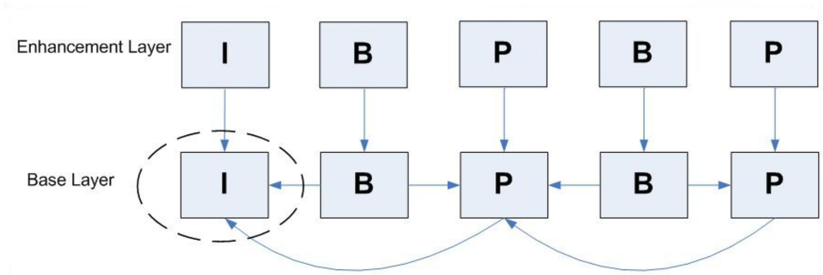


Fig. 1. GoP structure with frame dependences [21]. For instance, the circled I frame is an ancestor for the first B and P frames in the base layer and the I frame in the enhancement layer.

be summarized as follows [18]:

- Distortion impact - It represents the amount by which video distortion is reduced if this packet is successfully received at the decoder side. Video packets which belong to the same frame, $f$, have the same distortion impact, which is denoted by $v_f$. The distortion impact value, $v_f$, can be calculated for different frames and contents as in [29].
- Delay deadline - It represents the time by which the packet needs to be decoded at the destination. This is also known as decoding time stamp [5]. Video packets which belong to the same frame, $f$, have the same delay deadline, which is denoted by $d_f$.
- Dependence - As some frames are encoded based on the prediction of other frames, there are dependences among these frames. Hence, video packets decoding of one frame depends on the successful decoding of packets from other frames. The dependences among video packets of different frames are expressed using a directed acyclic graph [18], [21], as shown in Figure 1. As a result, each packet $k_f$ has a set of ancestors $\mathcal{A}_k^f$. Video packets, which belong to $\mathcal{A}_k^f$ $\forall f \in \mathcal{F}$, have higher distortion impact and smaller delay deadline than packet $k_f$.

### B. Video Transmission Model

Consider an uplink scenario where a mobile user captures live videos on his/her MT and transmits them for posting on the social network sites [5]. It is assumed that MTs are equipped with multiple radio interfaces and have multi-homing capabilities. As a result, an MT can establish communications with multiple wireless networks simultaneously and utilize them for video packet transmission. The employed radio interfaces are denoted by $\mathcal{N} = \{1, 2, \ldots, N\}$ with $N \geq 2$. Let $B_n$ denote the allocated bandwidth to the MT on the uplink using interface $n$. Let $g_n$ be the channel gain between the MT and the base station (BS) or access point (AP) communicating with radio interface $n$. Video packets which are delivered before their playback deadline are assumed to be successfully decoded at destination, i.e. we do not consider transmission errors.

At the beginning of every time slot, the MT should make a power allocation decision, $P_n$, for each radio interface $n$ and packet scheduling decision, $x_{kn}^f$, where $x_{kn}^f = 1$ if packet $k$ of frame $f$ is assigned to radio interface $n$, otherwise $x_{kn}^f = 0$. The video transmission decision policy regarding $P_n$ and $x_{kn}^f$ should be based on the video packet characteristics (i.e., distortion impact, delay deadlines, dependences among different packets), available opportunities at different radio interfaces (i.e., channel conditions and bandwidths), and the MT battery energy limitation. It is assumed that the channel gains, $g_n$ $\forall n \in \mathcal{N}$, remain constant within one time slot and varies from one time slot to another. Hence, it is sufficient to perform power allocation, $P_n$, on a time slot level instead of a packet level. The transmission energy for each time slot is limited by a transmission energy budget $E$ [19], which reflects the MT battery energy limitation. The energy budget per time slot $E$ should vary from one time slot to another depending not only on the MT energy limitation but also the current channel conditions for different radio interfaces. However, in the first step of research, we let $E$ be fixed over $\mathcal{T}$ independent of the channel conditions. Hence, in this work, $E$ is determined by dividing the MT available energy at the beginning of video transmission over the $T$ time slots.

## IV. Problem Formulation

In this section, we discuss the problem formulation for energy and content aware multi-homing video transmission in a heterogeneous wireless access medium. The objective is to minimize the video quality distortion, on a time slot level [5], under the MT energy constraint, through optimizing the power allocation to each radio interface and scheduling the most valuable video packets (packets with highest distortion impact) for transmission, while dropping the remaining ones if necessary. First, the problem is formulated as an MINLP which can be computationally intractable for a large-size problem. Hence, we employ a piecewise linearization approach and solve the problem using a cutting plane method which reduces the associated complexity from MINLP to a series of MIPs.

### A. MINLP Problem Formulation

The optimization framework aims to minimize the distortion in the perceived video quality given the MT battery energy limitation. The minimization of video quality distortion can be achieved through scheduling video packets with high distortion impact [18], [21] to the available multiple radio interfaces.

This is given by

$$V=\sum_{n=1}^{N}\sum_{k_f,f\in\mathcal{F}} v_f x^f_{kn}. \quad (1)$$

As videos are encoded using a fixed number of frames per second (fps), the difference in the delay deadline between any two consecutive frames is constant [5]. This delay difference is expressed by $|d_f - d_{f+1}| = \Delta D$. Since packets that belong to the same frame have the same delay deadline of the frame, the required minimum rate to transmit a video packet $k_f, \forall f \in \mathcal{F}$, is given by $r(k_f) = l_f/\Delta D$ [5]. The overall required data rate for packet transmission over a given radio interface $n$ should satisfy the achieved data rate over this interface, which is given by

$$\sum_{k_f,f\in\mathcal{F}} x^f_{kn} r(k_f) \le B_n \log_2(1+\frac{g_n P_n}{\eta_0 B_n}), \qquad \forall n\in\mathcal{N} \quad (2)$$

where $\eta_0$ denotes the noise power spectral density. In a case that the required data rate to transmit all the video packets is larger than the overall achieved data rate using all the radio interfaces given the MT battery energy limitation, packets with less distortion impact have to be dropped.

The total power allocation to the MT different radio interfaces should satisfy its battery energy limitation expressed by the specified energy budget per time slot $E$. This is described by the following constraint

$$\sum_{n=1}^{N} P_n \le \frac{E}{\tau}. \quad (3)$$

Video packet scheduling should capture the dependence relationship among different packets. Video packets whose ancestors are not scheduled for transmission should not be transmitted since they will not be successfully decoded at destination and hence waste both the MT and network resources. This can be described by a precedence constraint given by

$$x^f_{kn} \le x^{f'}_{k'n'}, \qquad \forall k'_{f'} \in \mathcal{A}^f_k, k_f \in \bigcup_{f\in\mathcal{F}} \mathcal{K}_f, n, n' \in \mathcal{N}. \quad (4)$$

In addition, a video packet can be assigned to one and only one radio interface, which is expressed by

$$\sum_{n=1}^{N} x^f_{kn} \le 1, \qquad \forall \mathcal{K}_f, f\in\mathcal{F}. \quad (5)$$

Hence, the energy and content aware multi-homing video transmission problem is given by

$$\begin{aligned} \max_{x^f_{kn},P_n} \quad & V \\ s.t. \quad & (2)-(5) \\ & x^f_{kn} \in \{0,1\} \\ & P_n \ge 0. \end{aligned} \quad (6)$$

The optimization problem (6) should be solved at the beginning of every time slot with a new GoP from different layers. The problem formulation takes into consideration the video packet characteristics in terms of distortion impact, delay deadlines, and packet dependence relation, the characteristics of the multiple wireless interfaces in terms of the channel conditions and the allocated bandwidth, and the MT battery energy limitation. Problem (6) is an MINLP as it involves the optimization over real variables $P_n$ and binary variables $x^f_{kn}$, and hence it is NP-hard [30], [31]. It can be computationally intractable to solve large instances of (6) (i.e., large number of video packets), and so in the following we aim to reduce the problem computational complexity.

### B. Piecewise Linearization Approach

Let $\Gamma_n = \frac{g_n}{\eta_0 B_n}$. The function $\log_2(1+\Gamma_n P_n)$ on the right hand side of (2) is a concave and continuous function that can be approximated with a set of piecewise linear functions using a first order Taylor expansion around points $P^h_n$, $h\in\mathcal{H}$ [32], where $\mathcal{H}$ denotes a set of all points in the domain of the logarithmic function. Hence,

$$\log(1+\Gamma_n P_n) \approx \min_{h\in\mathcal{H}}\{\log(1+\Gamma_n P^h_n)+\frac{\Gamma_n(P_n-P^h_n)}{1+\Gamma_n P^h_n}\}. \quad (7)$$

Hence, (2) can be approximated by

$$\sum_{k_f,f\in\mathcal{F}} x^f_{kn} r(k_f) \le \frac{B_n}{\log(2)}\{\log(1+\Gamma_n P^h_n)+\frac{\Gamma_n(P_n-P^h_n)}{1+\Gamma_n P^h_n}\}. \quad (8)$$

Rearranging (8) , we have

$$\begin{aligned} &\sum_{k_f,f\in\mathcal{F}} x^f_{kn} r(k_f) - \frac{B_n\Gamma_n}{\log(2)(1+\Gamma_n P^h_n)} P_n \le \\ &\frac{B_n}{\log(2)}\log(1+\Gamma_n P^h_n) - \frac{B_n \Gamma_n P^h_n}{\log(2)(1+\Gamma_n P^h_n)}, \\ &\qquad \forall n\in\mathcal{N}, h\in\mathcal{H}. \end{aligned} \quad (9)$$

As a result, problem (6) can be written as

$$\begin{aligned} \max_{x^f_{kn},P_n} \quad & V \\ s.t. \quad & (3)-(5),(9) \\ & x^f_{kn} \in \{0,1\} \\ & P_n \ge 0. \end{aligned} \quad (10)$$

The nonlinearity of (6) is eliminated by adding a large number of constraints using (9). This reduces the problem complexity from MINLP to a linear MIP. Although MIP is also NP-hard, there has been tremendous progress in MIP solution methods over the past decade that makes it possible to solve relatively large problems efficiently.

Ideally, we need all points $P^h_n$ in the domain of $\log(1+\Gamma_n P^h_n)$, $\mathcal{H}$, in order to approximate it. However, to find the optimal solution of (10), we only need an approximation of $\log(1+\Gamma_n P^h_n)$ around the optimal solution. Let $\widetilde{\mathcal{H}}$ denote a subset of $\mathcal{H}$. A cutting plane/constraint generation approach is employed to add the necessary constraints through (9). We start by an initial set of points $P^h_n$ with $h\in\widetilde{\mathcal{H}}$, and hence an initial set of constraints through (9), and the rest of points (constraints) are added as needed using the cutting plane algorithm [32], [33] given in Algorithm 1.

It has been proven in [32], [33] that the cutting plane algorithm is finite, as no cuts are repeated, and hence converges to the optimal solution of (6) in a finite number of iterations. While Algorithm 1 can efficiently solve (6), especially for a large-size problem, we need a powerful optimization solver to be available at the MT in order to solve (10), such as CPLEX [12], for the optimal power allocation and packet scheduling. Hence, in the next section, we aim to develop a greedy algorithm that has performance very close to the optimal solution and require simple operations. We will use Algorithm 1 to assess the performance of the proposed greedy algorithm.

**Algorithm 1** Cutting Plane Algorithm

**Initialization**: $P_n^h$, $h \in \widetilde{\mathcal{H}}$, $n \in \mathcal{N}$, $i = 1$, $j = 0$;
**while** $j = 0$ **do**
  Solve (10), and denote its solution as $(\bar{x}_{kn}^f(i), \bar{P}_n(i))$;
  **if** $\bar{P}_n(i) \notin P_n^h \ \forall h \in \widetilde{\mathcal{H}}$ **then**
    Append new cut to (10) using $P_n^{h+1} = \bar{P}_n(i)$;
    $i = i + 1$;
  **else**
    $j = 1$;
  **end if**
**end while**
**Output**: $\bar{x}_{kn}^f(i) \ \forall k \in \mathcal{K}, \forall f \in \mathcal{F}, \bar{P}_n(i) \ \forall n \in \mathcal{N}$.

## V. Energy and Content Aware Multi-homing Video Transmission Framework

Intuitively, the video quality distortion is minimized if more packets are transmitted and less are dropped. The higher the achieved data rates at different radio interfaces, subject to the MT battery energy limitation, the more transmitted packets and thus the better video quality. So, we propose to decouple problem (6) into two sub-problems. The first sub-problem is to find the allocated transmission power for each radio interface that maximizes the achieved data rate, subject to the MT battery energy limitation. The second sub-problem is to schedule the most valuable packets to different radio interfaces for transmission and drop the rest if necessary, given the transmission power allocation. The only difference between the exact problem solution and the approximate framework is that, the original MINLP performs joint power allocation and packet scheduling, while the proposed approach performs these two tasks separately. If the number of used radio interfaces is $N$, then the exact solution can insert a maximum of $N - 1$ additional packets more than the approximate framework, due to the joint optimization performed by the exact solution. Since it is not expected to use more than 2 to 5 radio interfaces, the number of additional inserted packets is small as compared to the approximate solution. With a large number of video packets per GoP, the contribution of these additional video packets to the achieved video quality is not significant. Hence, both exact and approximate solutions achieve very close results. This issue is further investigated in the numerical results of Section VI.

### A. Transmission Power Allocation for Each Radio Interface

The power allocation strategy adapts to the channel conditions and available bandwiths at different radio interfaces so as to maximize the achieved data rate for different radio interfaces while satisfying the MT battery energy limitation. Hence, we need to solve

$$\begin{aligned} \max_{P_n} \quad & \sum_{n=1}^{N} B_n \log_2(1 + \Gamma_n P_n) \\ s.t. \quad & (3) \\ & P_n \geq 0. \end{aligned} \tag{11}$$

Problem (11) has a concave objective function with linear constraint. As a result, problem (11) is a convex optimization problem and can be solved efficiently in polynomial time. Strong duality holds for problem (11) and a local maximum is a global maximum as well [34]. The Lagrangian function of (11) is expressed as

$$L(P_n, \lambda) = \sum_{n=1}^{N} B_n \log_2(1 + \Gamma_n P_n) + \lambda(\frac{E}{\tau} - \sum_{n=1}^{N} P_n) \tag{12}$$

where $\lambda$ is a Lagrangian multiplier that corresponds to the constraint of (3), with $\lambda \geq 0$. The dual function is given by

$$h(\lambda) = \max_{P_n \geq 0} L(P_n, \lambda) \tag{13}$$

and the dual problem of (11) is

$$\min_{\lambda \geq 0} h(\lambda). \tag{14}$$

The maximization problem of (13) can be written as

$$h(\lambda) = \sum_{n=1}^{N} \max_{P_n \geq 0} \{B_n \log_2(1 + \Gamma_n P_n) - \lambda P_n\}. \tag{15}$$

Thus, the optimal power allocation for each radio interface is obtained by solving

$$\max_{P_n \geq 0} \{B_n \log_2(1 + \Gamma_n P_n) - \lambda P_n\}. \tag{16}$$

For a fixed value of $\lambda$, the power allocation $P_n$ can be calculated for each radio interface by applying the Karush-Kuhn-Tucker (KKT) conditions on (16), which results in

$$P_n = \max\{\frac{B_n}{\lambda \ln(2)} - \frac{1}{\Gamma_n}, 0\}. \tag{17}$$

The optimal value of $\lambda$ that results in the optimal power allocation $P_n$ of (17) is determined by solving the dual problem of (14). The dual problem can be written as

$$\min_{\lambda \geq 0} \lambda(\frac{E}{\tau} - \sum_{n=1}^{N} P_n). \tag{18}$$

A gradient descent method can be used to calculate the optimal value for $\lambda$ [34], which is given by

$$\lambda(i+1) = \max\{\lambda(i) - \alpha(\frac{E}{\tau} - \sum_{n=1}^{N} P_n(i)), 0\} \tag{19}$$

where $i$ is an iteration index and $\alpha$ is a fixed sufficiently small step size. Since the gradient of (18) satisfies the Lipchitz continuity condition, the convergence of (19) towards the optimal $\lambda$ is guaranteed [34]. Hence, the power allocation $P_n$ of (17) converges to the optimal solution. The calculation of the optimal power allocation for each radio interface is described in Algorithm 2, where $\epsilon$ is a small tolerance.

**Algorithm 2** Transmission Power Allocation for Each Radio Interface

**Input**: $\Gamma_n$, $B_n$ $\forall n \in \mathcal{N}$, $E$, $\tau$, $\alpha$, $\epsilon$;
**Initialization**: $\lambda \geq 0$, $i = 1$, $P_n(0) = \{\}$, $j = 0$;
**while** $j = 0$ **do**
  **for** $n \in \mathcal{N}$ **do**
    $P_n(i) = \max\{\frac{B_n}{\lambda(i)\ln(2)} - \frac{1}{\Gamma_n}, 0\}$;
  **end for**
  **if** $|P_n(i) - P_n(i-1)| > \epsilon$ **then**
    $\lambda(i+1) = \lambda(i) - \alpha(\frac{E}{\tau} - \sum_{n=1}^{N} P_n(i))$;
    $i = i + 1$;
  **else**
    $j = 1$;
  **end if**
**end while**
**Output**: $P_n$ $\forall n \in \mathcal{N}$.

*B. Video Packet Scheduling for Multi-homing MTs*

The achieved data rate for each radio interface is $C_n = B_n \log_2(1 + \Gamma_n P_n)$, given the allocated transmission power $P_n$. Thus, the optimization problem (6) is reduced to

$$\begin{aligned} \max_{x_{kn}} \quad & V \\ s.t. \quad & \sum_{k_f, f \in \mathcal{F}} x_{kn}^f r(k_f) \leq C_n, \qquad \forall n \in \mathcal{N} \\ & (4) - (5) \\ & x_{kn}^f \in \{0, 1\}. \end{aligned} \tag{20}$$

Problem (20) is a binary program. It can be mapped to a new variant of the famous knapsack problem (KP) [13]. In this context, the available items are the video packets, $\mathcal{K}_f$ $\forall f \in \mathcal{F}$, the items weights are the required data rates, $r(k_f)$, and the profit associated with each item is the packet distortion impact, $v_f$. The problem has multiple knapsacks, since we have multiple radio interfaces, each with capacity $C_n$. Problem (20) resembles the multiple knapsack problem (MKP) [13], [14] in the absence of constraint (4). The precedence constraint of (4) is introduced due to the dependences among different video packets. A precedence-constrained knapsack problem (PC-KP) is studied only in literature for the case of single knapsack [13], [35]. To the best of our knowledge, there is no work in literature that studies a multiple knapsack problem with precedence constraints. Thus, in this paper we introduce a new variant of the knapsack problem and we refer to it as PC-MKP. Since PC-MKP contains MKP as a special case, and the latter is known to be NP-hard [13], PC-MKP is also NP-hard. Hence, we present a greedy algorithm that can solve the PC-MKP of (20) in polynomial time, which is based on the greedy algorithm of [14].

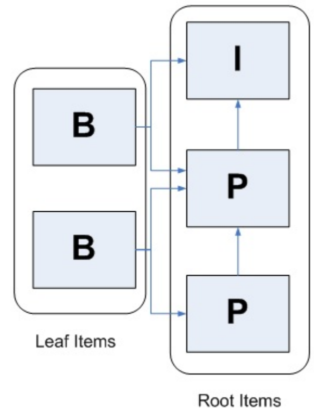


Fig. 2. Illustration of root and leaf items using base layer frames.

The proposed greedy algorithm consists of two parts. In the first part (A1), we aim to find a feasible solution for the problem through assigning items (video packets) to different knapsacks (radio interfaces) while considering their precedence constraints. Items are first classified into root and leaf items in order to find a feasible solution. This classification is illustrated in Figure 2 using video frames from the base layer. In general, root items have higher precedence order than leaf items. For video packet transmission, root items (packets of I and P frames) have higher distortion impact than leaf items (packets of B frames) [18].

The following two steps are used in A1 to find an initial feasible solution:

Step 1: First, root items are packed to different knapsacks as the leaf items cannot be packed without them; then leaf items are packed.

Step 2: Since items are packed in knapsacks in the order of their classification as root and leaf items, some of the early knapsacks may have residual capacity that can be used for packing some of the remaining leaf items whose root items have been packed in the previous step. Hence, the last part of A1 ensures that no residual capacity exists at any knapsack that can be used for packing the remaining leaf items.

In the second part (A2), we aim to improve the obtained feasible solution in A1. This is achieved by considering all pairs of packed items (video packets) and, if possible, interchanges them whenever doing so allows the insertion of an additional item (video packet) from the remaining ones (starting from root items to leaf ones), if all its ancestors are packed, into one of the knapsacks (radio interfaces).

We use the following notations: The feasible packet assignment for each radio interface is given by $\mathcal{G}_n$ $\forall n \in \mathcal{N}$. Letting $\mathcal{S} = \bigcup_{n=1}^{N} \mathcal{G}_n$, $\mathcal{L} = \bigcup_{f \in \mathcal{F}} \mathcal{K}_f - \mathcal{S}$ is a set of remaining unassigned video packets. Let $R_n$ be the current used capacity for each radio interface (thus, the remaining capacity is $O_n = C_n - R_n$), and $h_{kf}$ is an index of the radio interface where packet $k_f$ is currently assigned to. Algorithm 3, describes video packet scheduling for multi-homing MTs.

It is assumed in Algorithm 3 that video packets are sorted according to their classification as root and leaf items. In

A2 of Algorithm 3, $\mathcal{S}, \mathcal{L}, O_n$, and $h_{kf}$ are supposed to be updated whenever some $\mathcal{G}_n$ is updated. Let the total number of available video packets from the current time slot be $K$. The complexity of A1 is $O(KN)$ and A2 is $O(K^2)$. Thus, Algorithm 3 has polynomial time complexity.

**Algorithm 3** Video Packet Scheduling for Multi-homing MTs

**A1: Finding a Feasible Solution**
**Initialization**: $\mathcal{L} \longleftarrow \bigcup_{f\in\mathcal{F}} \mathcal{K}_f$, $R_n \longleftarrow 0, \mathcal{G}_n = \{\}\ \forall n \in \mathcal{N}$;
**for** $n \in \mathcal{N}$ **do**
  **for** $k_f \in \mathcal{L}$ **do**
    **if** $x^{f'}_{k'n'} = 1\ \forall k'_{f'} \in \mathcal{A}^f_k, n' \in \mathcal{N},\ r(k_f) + R_n \leq C_n$ **then**
      $x^f_{kn} = 1,\ R_n = R_n + r(k_f)$;
    **end if**
    $\mathcal{G}_n = \mathcal{G}_n \cup \{k_f\}$;
  **end for**
  $\mathcal{L} = \mathcal{L} - \mathcal{G}_n$;
**end for**
**for** $n \in \mathcal{N}$ and $O_n > \min\{r(k_f)|k_f \in \mathcal{L}\}$ **do**
  **for** $k_f \in \mathcal{L}$ **do**
    **if** $x^{f'}_{k'n'} = 1\ \forall k'_{f'} \in \mathcal{A}^f_k, n' \in \mathcal{N},\ r(k_f) + R_n \leq C_n$ **then**
      $x^f_{kn} = 1,\ R_n = R_n + r(k_f)$;
    **end if**
    $\mathcal{G}_n = \mathcal{G}_n \cup \{k_f\}$;
  **end for**
  $\mathcal{L} = \mathcal{L} - \mathcal{G}_n$;
**end for**
**A2: Improving the Feasible Solution**
**for** $k1 \in \{k_f|k_f \in \mathcal{S}, O_{h_{kf}} + \max_{n\neq h_{kf}} O_n \geq \min_{k'_{f'}\in\mathcal{L}} r(k'_{f'})\}$ **do**
  **for** $k2 \in \{k_f|k_f \in \mathcal{S}, k_f > k1, h_{kf} \neq h_{k1}, O_{h_{k_f}} + O_{h_{k1}} \geq \min_{k'_{f'}\in\mathcal{L}} r(k'_{f'})\}$ **do**
    $W(u) = \max\{r(k1), r(k2)\}$, $W(q) = \min\{r(k1), r(k2)\}$;
    $i_u = h_u$, $i_q = h_q$, $\delta = W(u) - W(q)$;
    **if** $\delta \leq O_{i_q}$ and $O_{i_u} + \delta \geq \min_{k'_{f'}\in\mathcal{L}} r(k'_{f'})$ **then**
      $v_c = \max\{v_{k'_{f'}}|k'_{f'} \in \mathcal{L}, r(k'_{f'}) \leq O_{i_u} + \delta, \mathcal{A}^{f'}_{k'} \subset \mathcal{S}\}$;
      $\mathcal{G}_{i_u} = (\mathcal{G}_{i_u} - u) \cup \{q, c\}$, $\mathcal{G}_{i_q} = (\mathcal{G}_{i_q} - q) \cup \{u\}$;
    **end if**
  **end for**
**end for**

## VI. Numerical Results

This section presents numerical results for the energy and content aware multi-homing video transmission, of one GoP, in a heterogeneous wireless access medium. Video sequences are compressed at encoding rate of 30 fps [21], [27], and the GoP structure is composed of 12 frames [36] from one layer (base layer) with one B frame between P frames. Thus, the time slot duration $\tau$ is set to 400 milli-second. Each encoded frame has a variable length 6000 - 9600 bits [27]. Specifically, for the GoP under consideration, the frame length is 9600 bits for I frames, 8000 bits for P frames, and 6000 bits for B frames. Each I frame is encoded into 12 packets, while each of B and P frames are encoded into 10 packets. The decoder time stamp difference, $\Delta D$, between two successive frames is 40 milli-second [5]. Hence, each I or P packet requires data rate $r(k_f)$ of 20 Kbps, while an B packet requires a data rate of 15 Kbps. The packet distortion impact values are $v_f = 5$ for I frames, $v_f = 4$ for P frames, and $v_f = 2$ for B frames [21]. Two radio interfaces are utilized for video transmission ($\mathcal{N} = \{1, 2\}$). The system unit bandwidth is 363 KHz. In the numerical results, the proposed energy and content aware multi-homing video transmission framework, the greedy approach (GA), is compared with the exact solution using the cutting plane approach (CPA). The MIPs of the CPA are solved using the CPLEX solver through GAMS [12]. The GA is also compared with two benchmarks. The first benchmark is an energy independent approach (EIA), where problem (10) is solved without the MT battery energy constraint of (3). The second benchmark is an earliest deadline first approach (EDFA), which is a common benchmark for video packet scheduling [21]. In the EDFA, packets whose deadline is closer are scheduled earlier. Hence, the EDFA is content independent, unlike the GA which first schedules packets with higher distortion impact. In order to determine the power allocation for each radio interface in the EDFA, we employ an equal power allocation approach (EPA) [38], where the energy budget per time slot, $E$, is distributed equally between the two radio interfaces.

Numerical results are studied for multi-homing video transmission of a GoP over one time slot. Two sets of results are presented. In the first set of results, given by Figures 3 and 4, the energy budget per time slot, $E$, is varied from 10 to 120 milli-joule, which is equivalent to a video transmission duration of 120 to 10 minutes given an MT battery available energy of 180 Joule[1]. For the time slot under consideration, the channel gain is given by $g_1 = 0.5019$ and $g_2 = 0.448$ for the two radio interfaces, and the allocated bandwidth is 1 unit from the first radio interface and 2 units from the second radio interface. The background noise power, $\eta_n = \eta_0 B_n$, is equal to 0.01 watt for the first radio interface [39], and 0.02 watt for the second radio interface. In the second set of results, given by Figures 5 and 6, the energy budget per time slot is fixed at $E = 170$ milli-joule while the channel gain for the first radio interface is varied. For these results, the channel gain for the second radio interface is fixed at $g_2 = 0.448$, the allocated bandwidth is 1 unit from each radio interface, and the background noise power for both radio interfaces is $\eta_n = 0.01$, $n \in \mathcal{N}$. In the numerical results, the video quality metric is defined as the distortion impact ratio of the transmitted packets to the total packets.

Figure 3 shows the video quality versus the energy budget per time slot $E$. In general, as expected, as $E$ increases, more transmission power can be allocated to both radio interfaces,

[1]A blackberry Lithium Ion battery is 900 mAh and 3.7 Volt, i.e. the battery capacity is 11988 J.

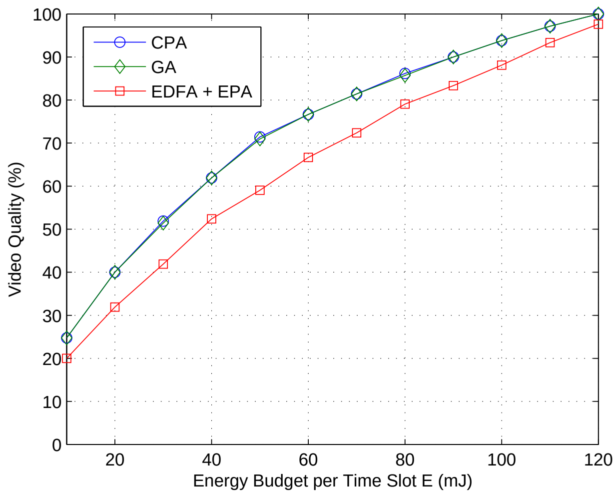


Fig. 3. The achieved video quality using variable energy budget per time slot $E$. The channel gain $g_1 = 0.5019$ and $g_2 = 0.448$. The allocated bandwidth $B_1 = 1$ unit and $B_2 = 2$ units. The background noise power, $\eta_1 = 0.01$ watt and $\eta_2 = 0.02$ watt.

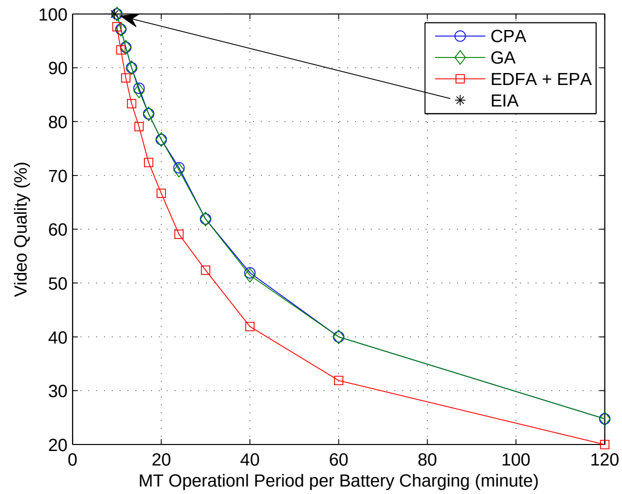


Fig. 4. The trade-off between the achieved video quality and the MT operational period per battery charging. The channel gain $g_1 = 0.5019$ and $g_2 = 0.448$. The allocated bandwidth $B_1 = 1$ unit and $B_2 = 2$ units. The background noise power, $\eta_1 = 0.01$ watt and $\eta_2 = 0.02$ watt.

which results in higher transmission data rates and hence more transmitted packets. The CPA and the GA exhibit very close performance in terms of the perceived video quality. This demonstrates the effectiveness of the GA, whose performance is very close to that of the CPA (the exact solution) but with reduced computational complexity. The main difference between the CPA and the GA is that the CPA jointly optimizes the transmission power allocation and the video packet scheduling. Hence, in the CPA, the transmission capacities of different radio interfaces are determined so as to assign as many valuable video packets as possible in order to minimize the video quality distortion. On the other hand, the GA maximizes the transmission capacity for each radio interface and then performs video packet scheduling. As a result, unlike the CPA, one packet may not fit in any of the radio interfaces although the sum of the residual capacities in both radio interfaces is enough to transmit this packet. This is the reason that the CPA has a slightly higher performance for different $E$ values as compared to the GA. However, this is always corresponding to a maximum of one additional packet insertion and its contribution to the total video quality is not significant, as shown in the figure. In general, for $N$ radio interfaces, the CPA can insert a maxmium of $N-1$ additional packets as compared to the GA. With a large number of available video packets, the impact of the additional video packets on the achieved video quality is not significant. The EDFA with EPA achieves lower performance than the content aware approaches (CPA and GA) as it does not schedule packets according to their distortion impact. At a high $E$ ($E > 100$ milli-joule), both the content aware approaches and the EDFA have sufficient energy budget so that almost all video packets are scheduled for transmission, hence the difference in the scheduling policies (i.e. which packets are dropped) is not significant, which results in the close performance.

Figure 4 shows the video quality versus the MT operational period per battery charging. In general, requiring high video quality results in a lower operational period for the MT (less than 20 minutes). However, as shown in figure, the content aware approaches can achieve the same video quality as the EDFA, but at a longer MT operational period per battery charging. For the energy independent approach (EIA), the achieved video quality is always $100\%$, yet the consumed energy per time slot is always 120 milli-watt. This is equivalent to a video duration of $9.5$ minutes given the MT available energy ($180$ Joule). On the other hand, the GA offers a choice for desirable trade-off between the video quality and the consumed energy per time slot $E$. Hence, while the GA can provide a variable video quality ranging from $25 - 100\%$ for a total duration of $120 - 10$ minutes, the energy independent approaches present only a fixed video quality for a short MT operational period.

Figure 5 shows the video quality versus the channel gain of the first radio interface $g_1$. The figure gives a comparison among the GA, the content aware (CA) approach based on Algorithm 3 using an EPA for transmission power allocation (instead of Algorithm 2 as in the GA), and the EDFA (which is content independent) with EPA. In general, since the EPA approach (for both CA and EDFA) allocates transmission power independent of the channel condition, the achieved transmission capacity is lower than that of the GA at a poor channel condition. This results in an improvement in video quality for the GA as compared with the CA and EDFA with EPA at a poor channel condition. As the EDFA is content independent, it achieves a lower video quality than the CA approach. With an improved channel quality ($g_1 > 0.03$), the CA approach with EPA can achieve performance close to that of the GA. The transmission power allocation for each radio interface (R1 and R2) versus the channel gain of the first radio interface is given in Figure 6. The EPA has a fixed power allocation independent of the channel condition. On

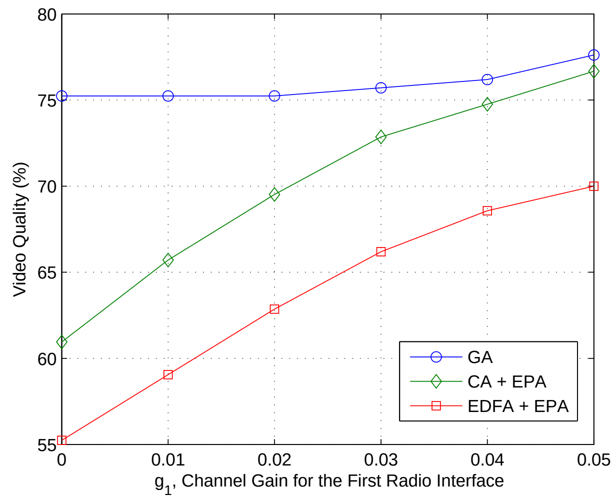


Fig. 5. Video quality performance for a varying channel gain. The channel gain $g_2 = 0.448$. The allocated bandwidths $B_1$ and $B_2$ are 1 unit from each radio interface. The background noise power for both radio interfaces is $\eta_n = 0.01$.

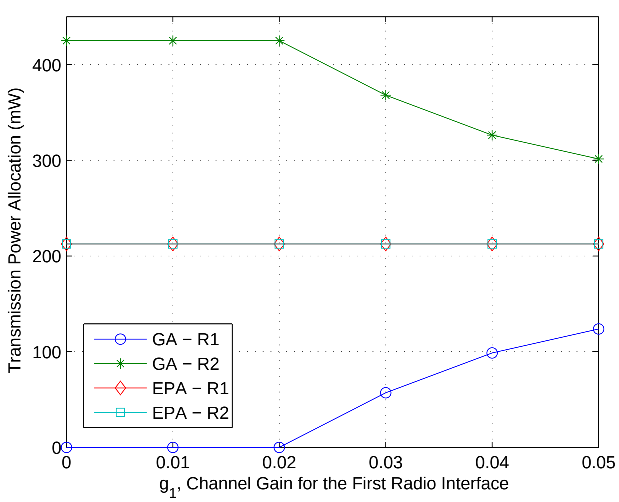


Fig. 6. Transmission power allocation for varying channel gain. The channel gain $g_2 = 0.448$. The allocated bandwidths $B_1$ and $B_2$ are 1 unit from each radio interface. The background noise power for both radio interfaces is $\eta_n = 0.01$.

the other hand, the GA adapts its power allocation for each radio interface based on the channel condition for the interface, hence maximizing the achieved transmission capacity and the achieved video quality.

## VII. Conclusion

In this paper, energy and content aware multi-homing video transmission is investigated for a heterogeneous wireless access medium. The objective is to perform power allocation and video packet scheduling for different radio interfaces so as to minimize the perceived video quality distortion with an acceptable computational complexity. The newly proposed energy and content aware video transmission framework offers a desirable trade-off between the perceived video quality and the MT operational period. The energy and content aware multi-homing video transmission problem formulation is based on an MINLP which can be computational intractable for an expected large number of video packets. A piecewise linearization approach is employed to reduce the problem complexity from MINLP to a series of MIPs, which is very efficient for a large-size problem. For practical implementation in MTs, a greedy approach (GA) is proposed to perform the power allocation and packet scheduling in polynomial time complexity. The GA separates the problem into two stages. Overall, the solutions of the proposed sub-problems consume much less power than the power used for video packet transmission. The GA first stage optimizes the allocated power for each radio interface given the interface available bandwidth, channel condition, and the MT battery energy constraint. The second stage performs video packet scheduling to different radio interfaces so as to minimize the resulting video quality distortion. We map the packet scheduling problem for multi-homing video transmission to a new variant of the knapsack problem, namely PC-MKP, and solve it in polynomial time complexity of the problem parameters in terms of the number of radio interfaces and the number of video packets using a greedy algorithm. Numerical results demonstrate that the proposed framework has performance very close to the exact solution yet at a reduced computational complexity. For further work, we aim to support a variable energy budget per time slot $E$ that depends on both the MT current available energy and the channel conditions, in order to achieve more energy efficient video transmission with improved QoS and a longer MT operational period.

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