Distributed Scheduling for Video Streaming over Multi-Channel Multi-Radio Multi-Hop Wireless Networks

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***Abstract*— An important issue of supporting multi-user video streaming over wireless networks is how to optimize the systematic scheduling by intelligently utilizing the available network resources while, at the same time, to meet each video's QoS (Quality of Service) requirement. In this work, we study the problem of video scheduling over multi-channel multi-radio multi-hop networks with the goals of minimizing the video distortion. At first, we construct a general distortion model according to the network's transmission mechanism, as well as video's rate-distortion characteristics. Then, by joint considering the channel assignment, rate allocation and routing, we develop a fully distributed scheduling scheme to get an optimal QoS performance. Furthermore, the realization of the distributed scheduling scheme through cooperation among the channel, link and source is the highlight of this paper. Extensive simulation results are provided which demonstrate the effectiveness of our proposed scheme.**

***Index Terms*— multi-radio multi-channel multi-hop; wireless networks; distributed scheduling; video; QoS.**

I. INTRODUCTION

THE problem of video scheduling over multi-channel multi-radio multi-hop networks is, compared to traditional data communications in wireless multi-hop networks, further complicated by the heterogeneity in both the network conditions and the application contents, including i) **channel-assignment**: what are the set of channels that each link should be operated on? ii) **rate allocation**: how to allocate the appropriate rate to the given channels and links? and iii) **routing**: how to select the potential channels that minimize total video distortion? These three problems are interact with each other, and thus form a challenging cross-layer control problem across the MAC layer and the application layer. For ease of exposition, in the rest of the paper whenever there is no source of confusion, we will use of the term "scheduling" to refer to the combined action of channel assignment, rate allocation and routing.

Our objective is to propose a distributed video scheduling scheme in multi-channel multi-radio networks so as to minimize the total video's distortion. Specifically, the scheduling problem is formulated as a united convex optimization based on the distortion model according to the network's transmission mechanism, as well as video's rate-distortion characteristic, and is then solved by joint considering the channel assignment, rate allocation and routing. Although some scheduling protocols can be obtained via extending the current throughput-optimal algorithms in [1]–[4], which are known to achieve the maximum system capacity for multi-channel multi-radio networks. However, these works focus on optimal system throughput or scheduling efficiency and don't care about the transmission content. In addition, these works target at elastic data transmission, where users do not have stringent deadline constraints. Therefore, due to the characteristics of video content and the deadline requirement of video applications, these solutions may not be optimal for delivering multi-user, delay-constrained video applications. To the best of our knowledge, this work is the first one to consider the problem of video scheduling in multi-channel multi-radio multi-hop networks.

The rest of paper is organized as follows. Section II introduces the distortion model of the video and network. In Section III, we formulate the scheduling as a convex optimization problem, and propose a distributed minimum-distortion scheduling scheme for multiple video streaming sessions sharing multi-channel multi-radio networks. And then, some simulation results and comparisons are provided for our proposed scheme in Section IV. Section V concludes the paper.

II. SYSTEM MODEL

In this paper, we employ an additive model to capture the total video distortion as our previous work [5]. The overall distortion D_{all} is:

$$D_{all} = D_{comp} + D_{loss}, \tag{1}$$

where the distortion introduced by source compression is denoted by D_{comp}, and the additional distortion caused by packet loss is denoted by D_{loss}. Specifically, D_{comp} can be approximated by [5]:

$$D_{comp} = \frac{\theta}{R - R^0} + D^0, \tag{2}$$

Likewise, D_{loss} can be modeled by a linear model related to the packet loss rate P_{loss} [6]:

$$D_{loss} = \alpha P_{loss}, \tag{3}$$

where R is the rate of the video stream, θ, R^0 and D^0 are the parameters of the distortion model [5], and α depends on parameters related to the compressed video sequence [6]. In what follows, we study P_{loss} in the context of a specific wireless network.

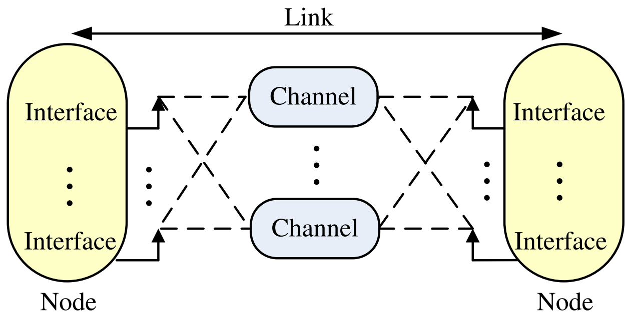


Fig. 1. Basic network model.

Consider a multi-channel multi-radio wireless network with $\mathbf{N} = \{1, ...n..., N\}$ nodes, $\mathbf{L} = \{1, ...l..., L\}$ links, N_f non-overlapping frequency channels and each node $n \in \mathbf{N}$ is equipped with N_n network interfaces. The basic network model is illustrated in Fig. 1. In order to take into account possible channel diversity, we denote r_l^c as the rate at link $l \in \mathbf{L}$ can transfer data on channel c, provided that there are no interfering links transmitting on channel c at the same time. Besides, there are $\mathbf{S} = \{1, ...s..., S\}$ users in the system, and each user $s \in \mathbf{S}$ is associated with a source node and a destination node. The traffic from each user may be routed over multiple alternate paths. Let $[M_{sj}^l]$ denote the routing matrix, where $M_{sj}^l = 1$ if path j of user s employs link l, $M_{sj}^l = 0$, otherwise. Let $N(s)$ denote the number of alternate paths for user s, and F_{sj} the fraction of traffic from user s that is routed to path j. Further, let $\mathbf{Q} = [Q^c]$ denote the outcome matrix of the routing scheme, where Q^c is the set of non-interfering links that are chosen to transmit data in channel c. We denote *Link Balance Ratio (LBR)* [8] u_l as the fraction of link input r_l^{in} and link output r_l^{out} for link l:

$$u_l = r_l^{in}/r_l^{out}, \tag{4}$$

where

$$r_l^{in} = \sum_{s=1}^{S}\sum_{j=1}^{N(s)} M_{sj}^l F_{sj} R_s, \tag{5}$$

and

$$r_l^{out} = \sum_{c:l\in Q^c} r_l^c, \tag{6}$$

R_s in (5) represents the video rate of user s.

Considering the interference relationship, for each link l, it is assumed that there is a set $\mathbf{I}_l$ of links that interfere with l. That is, if link l and another link in $\mathbf{I}_l$ are transmitting on the same channel at the same time, neither of the links can transfer data, which is similar to the CSMA/CA mechanism used in 802.11 networks [8]. We assume that each radio can only tune to one channel at any given time and switch channels dynamically as in [2]. Therefore, for link l to successfully communicate on channel c, both the sending and receiving nodes muse tune one radio to channel c. In this case, the total *LBR* in $\mathbf{I}_l$ can be defined as:

$$u_{\mathbf{I}_l} = \sum_{l'\in\mathbf{I}_l} u_{l'}. \tag{7}$$

Congestion over each wireless link is measured as the average delay for all packets traversing that link. Following the classic M/G/1 queuing model, average packet delay over a link is inversely proportional to the *Potential Transmission Ability (PTA)* [7]. So, we can set *PTA* of link l as:

$$PTA_l = r_l^{out}/(u_{\mathbf{I}_l} - \gamma), \tag{8}$$

where $\gamma > 1$ is an over-provisioning factor. Therefore, we can model the average packet delay for path j of user s[1]:

$$E\{Delay\} = \sum_{l=1}^{L} \frac{(u_{\mathbf{I}_l} - \gamma)}{r_l^{out}} \cdot \omega \cdot M_{sj}^l, \tag{9}$$

where ω is the average packet size. Following the M/G/1 model, we can get:

$$\begin{aligned} Pr\{Delay > T\} &= \exp\Big\{-\frac{T}{E\{delay\}}\Big\} \\ &= \exp\Bigg\{-\frac{T}{\sum\limits_{l=1}^{L}\frac{(u_{\mathbf{I}_l}-\gamma)\cdot\omega\cdot M_{sj}^l}{r_l^{out}}}\Bigg\}. \end{aligned} \tag{10}$$

Taking into account the average packet loss rate P_B due to transmission errors, the total packet loss rate for path j of user s is then:

$$P_{loss} = P_B + (1 - P_B)Pr\{Delay > T\} \tag{11}$$

The total distortion for path j of user s from packet loss can be expressed as

$$D_{loss} = \alpha P_{loss} = \alpha\Bigg(P_B + (1-P_B)\exp\Big\{-\frac{T}{\sum\limits_{l=1}^{L}\frac{(u_{\mathbf{I}_l}-\gamma)\cdot\omega\cdot M_{sj}^l}{r_l^{out}}}\Big\}\Bigg). \tag{12}$$

III. Distributed Minimum-Distortion Scheduling Scheme

Based on the previous discussions, we seek a joint optimal scheduling outcome $\mathcal{M}$ to achieve the overall minimum video distortion:

$$\min_{\mathcal{M}} \quad \Big\{D_{all} = \sum_{s=1}^{S}\sum_{j=1}^{N(s)}\big(\frac{\theta_s}{R_s - R_s^0} + D_s^0 + D_{loss}\big)\Big\} \tag{13}$$

subject to

$$r_l^{out} = \sum_{c:l\in Q^c} r_l^c \le \sum_{s=1}^{S}\sum_{j=1}^{N(s)} M_{sj}^l F_{sj} R_s = r_l^{in}, \tag{14}$$

$$N(s) \ge 1, F_{sj} \ge 0, \sum_{j=1}^{N(s)} F_{sj} = 1, \tag{15}$$

$$R_s \ge 0, n \ge 1, r_l^c \ge 0, \tag{16}$$

where θ_s, R_s^0 and D_s^0 in (13) are the corresponding parameters for user $s \in \mathbf{S}$. Intuitively, the reconstructed video quality

[1]In practice, congestion may be a more complicated function of rate as predicted by M/G/1 model. However, this expression can be viewed as an approximation of the average link delay, capturing the non-linear increase of delay with total channel time utilization.

is effected by the user's source rate R_s, the channel rate r_l^c, and the routing information $[M_{sj}^l]$. As mentioned before, this scheduling problem is implicitly coupled with a channel assignment, a rate allocation problem and a multi-path routing problem. In this section, we propose a Distributed Minimum-Distortion Scheduling (DMDS) scheme where each source, each link and each channel solve their own problem through efficient cooperation.

A. Design Guild

In the processing of channel assignment, we focus on every node to select "optimal channels" to achieve minimum video distortion. However, it is difficult to define the "minimum video distortion" in the process of channel assignment. Hence, we map the index of "minimum video distortion" to "optimal network congestion"[2]. Specifically, we present a linear programming (17) method to obtain approximate solutions of optimal channel assignment. In this formulation, we define $(r_l^{in} - r_l^{out})$ as the factor of network congestion, and corresponding constraints remain identical to (15) and (16).

$$\min \quad \sum_{l \in \mathbf{L}} (r_l^{in} - r_l^{out}) \tag{17}$$

Concerning with the routing and rate allocation, we employ multi-path routing with the goal of finding multiple potential paths to minimize the total system congestion induced by each video user. We consider dividing the total rate increment of each video stream $\triangle R_s$ into k ($k \in [1, K]$) small increments (corresponding to $N(s)$ paths described in Section II) such that $\triangle R_s = \sum_{k=1}^{K} \triangle R_s^k$ as in [7]. According to [7], for each increment k, the packet loss distortion increment $\triangle D_{loss}^k$ and the video compression distortion reduction $\triangle D_{comp}^k$ can be obtained:

$$-\triangle D_{comp}^k \approx \frac{\theta_s}{(R_s - R_s^0)^2} \triangle R_s^k. \tag{18}$$

$$\triangle D_{loss}^k \approx \alpha(1 - P_B) \sum_{l \in \mathbf{L}} \frac{\triangle R_s^k}{PTA_l}. \tag{19}$$

Given the $\triangle D_{loss}^k$ and $\triangle D_{comp}^k$, the source node can make the rate allocation decision by comparing the two quantities. The allocated rate will be increased by $\triangle R_k^s$ until $-\triangle D_{comp}^k > \triangle D_{loss}^k$, i.e., when the benefit of distortion reduction is no longer worthwhile the consequential network congestion. Therefore, the rate control algorithm can continue until it reaches the optimal rate that strikes a balance between the two trade-off slopes.

B. DMDS Scheme

The key challenges in designing DMDS are how to select optimal channels, paths as well as allocated rates to ensure the resulting system is both stable and optimal. We illustrate the interplay between the source, link and channel in Table I. For DMDS, each channel computes the congestion weight to make the channels assigned to spatially close nodes as different as possible, each link calculates the rates to strike a balance between the rate increment and network congestion, and each source determines the optimal path distribution to achieve minimum video distortion. Specifically, congestion weight message is fed back from the channels to the links to avoid network congestion, queue length message is from the links to the sources to prevent the source rates from exceeding the transmission ability, and rate allocation and routing message is from the sources to the links to achieve the optimal performance.

TABLE I
THE DMDS SCHEME

At each time slot t:

• **Source s:** determine the optimal path distribution for each source

$$\max_{F_s} \quad -\sum_j (F_{sj})^2 - \sum_j F_{sj} \sum_l M_{sj}^l q_l(t)$$

where $F_s = [F_{s1}..., F_{sj}, ...F_{sNs}]$, $F_{sj} \geq 0$,
and $q_l(t)$ denotes the queue length for link l at time slot t;

Queue Length Update:
$q_l(t+1) = [q_l(t) + \lambda_q(t)\big(\sum_s \sum_j M_{sj}^l F_{sj} R_s^j(t) - \sum_c r_l^c(t)\big)]^+$
where $[x]^+ = \max(x, 0)$, and $\lambda_q(t)$ is the step size.

• **Link l:** determine the optimal traffic in each link

$$\min \quad \sum_l \frac{\triangle R_s^k(t)}{PTA_l}$$

Rate Increment Update:
$\triangle R_s^k(t+1) = [\triangle R_s^k(t) + \lambda_R(t)\big(\sum_k \triangle D_{loss}^k - \triangle D_{comp}^k\big)]^+$
where $\lambda_R(t)$ is the step size.

• **Channel c:** determine the minimum congestion in each channel

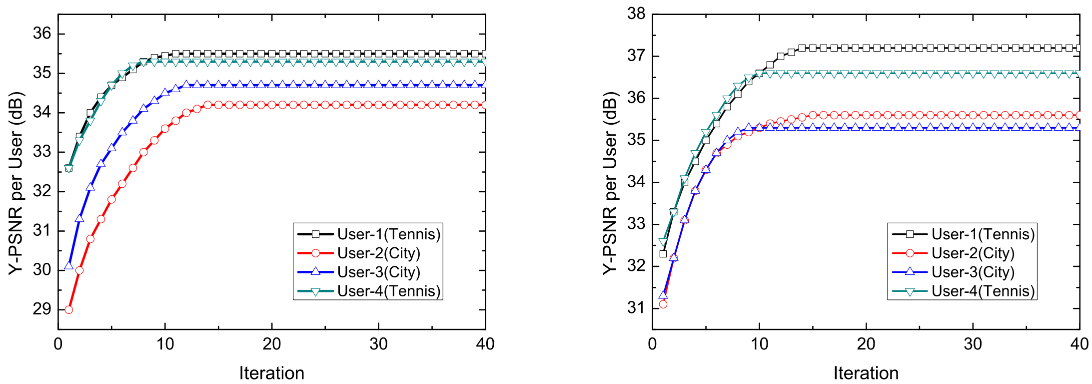
$$\min \quad \sum_l (r_l^{in} - r_l^{out})$$

Congestion Weight Update:
$u_l^c(t+1) = u_l(t+1)/r_l^c(t+1)$.

DMDS proceeds first by determining the available paths between the source and destination, and then by deciding paths according to the minimum distortion. It proceeds in two phases, the path discovery and path reservation phases, respectively. To this aim, control messages are exchanged between the source and the destination via forwarding by the intermediate nodes. In order to derive exact bounds on the performance of our DMDS scheme, we assume that the control channel is reliable, and that nodes are synchronized (i.e., there is a bounded time interval in which all nodes receive all dedicated control packets).

The sources send all outgoing links with path discovery messages, which are forwarded by the intermediate nodes on the control channel. At each intermediate node, the path discovery messages contain the information of congestion weight and queue length related to every possible stream between the source and intermediate node. This intermediate node then extends the path as the source does. Upon reception of path discovery messages from the destinations,

[2]The stream rate is fixed in the process of channel assignment, so D_{comp} is not changed in this process.



(a) $N = 10$, $L = 15$, $N_f = 2$, $N_n = 2$

(b) $N = 15$, $L = 30$, $N_f = 3$, $N_n = 3$

Fig. 2. Plots of PSNR versus time for the first frame of each video in different simulation settings (step sizes: $\lambda_q = 4 \times 10^{-5}$, $\lambda_R = 2 \times 10^{-5}$).

the sources determine the possible paths between the sources and destinations based on explicit feedback from the links, in form of queue length, rate increment and congestion weight. In particular, the source minimizes the total distortion while balancing the congestion of channels and links. In fact, it is similar to the standard TCP dual algorithm except that the maximization problem is conducted over a vector not a scalar, to reflect the multi-path nature of DMDS.

Remark: From Table I, it can be found that the computations at the sources are linear with the number of sources, while the computations at the links and channels do not grow with the number of the sources. In addition to computation overhead, there are three new functionalities required by DMDS. Firstly, DMDS will require MPLS (Multi-Protocol Label Switching) for splitting traffic over multiple paths. Secondly, DMDS will require frequent link-load measurements which are possible using SNMP (Simple Network Management Protocol). Finally, DMDS requires an explicit limit rate of the incoming traffic, and this can be achieved by dropping packets sent above the allowed rate.

C. Stability and Optimality Results

In this section and Appendix, we provide the analytical derivation and theoretical foundation of the DMDS scheme.

Proposition 1: DMDS scheme converges to the joint global optimum $\mathcal{M}$ of (13) for sufficiently small queue length step size λ_q and rate increment step size λ_R.

Outline of the Proof: The idea of DMDS scheme is to decouple the coupled objective function in (13) by introducing auxiliary variables and additional constraints, and then use Lagrange dual decomposition to decouple all of the constraints. There are two exact steps: i) introducing new variables to enable decoupling; ii) employing dual decomposition and gradient descent method to derive the DMDS sheme. See Appendix for the detailed proof. ■

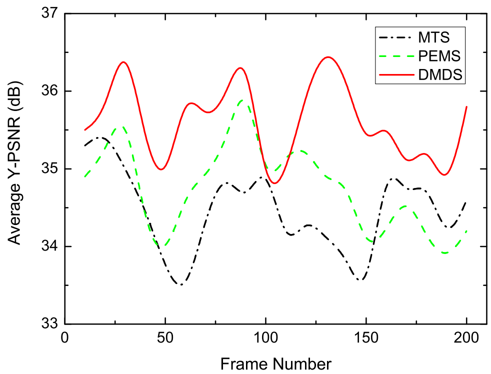
Given the dynamic nature of DMDS, it is natural to wonder whether it would also behave well with stochastic variations in traffic. Consider streams arriving according to a Poisson process with exponentially-distributed file sizes. A stream leaves the network after it finishes transmitting a file. The service rates are determined by the solution of DMDS scheme. Note that streams may arrive and depart even before the DMDS scheme converges, i.e., we do not assume time-scale separation between scheme convergence and stochastic stability of DMDS: whether the number of active sessions and the sizes of the queues in the network remain finite for DMDS in such dynamic environment. The answer is positive, as summarized in the following theorem, whose proof can be found in [9].

Proposition 2: The DMDS scheme is stochastically stable if the average output in each link is smaller than its input, i.e. the stochastic region of DMDS is the largest possible one: the interior of the feasible region of problem (13).

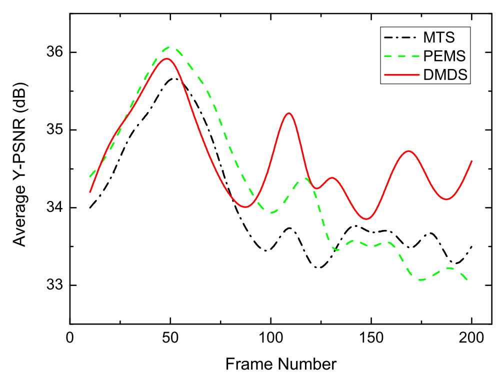
Outline of the Proof: The key idea is to show that dual variables as scaled versions of queue lengths, and then to show that the DMDS scheme follows as a special case of dual-based algorithms for generalized minimal distortion whose stochastic stability has been established. ■

IV. Simulation Results and Discussions

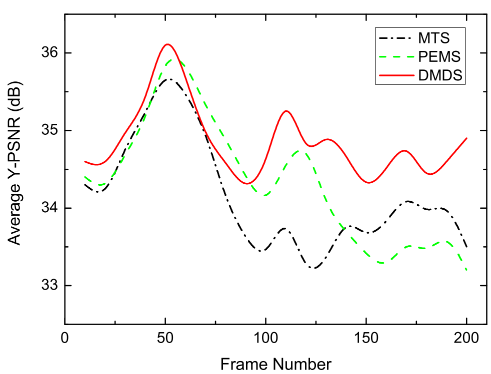
In this section, we conduct simulation experiments to study the performance of the proposed DMDS scheme in multi-channel multi-radio multi-hop wireless networks. To simulate the video applications, two HD (High-Definition) sequences (*City* and *Tennis*) are used to represent video with dramatically different levels of motion activities. In terms of HD video, the sequence has spatial resolution of 1280×720 pixels, and the frame rate of 60 frames per second. Video stream is encoded using a fast implementation of H.264/AVC codec at at various quantization step sizes, with GOP (Group Of Pictures) length of 25 and *IBBP*... structure similar to that often used in MPEG-2 bitstreams. Encoded video frames are segmented into packets with maximum size of 1500 bytes, and the transmission intervals of each packet in the entire GOP are spread out evenly, so as to avoid unnecessary queuing delay due to the large sizes of intra coded frames. In the following,



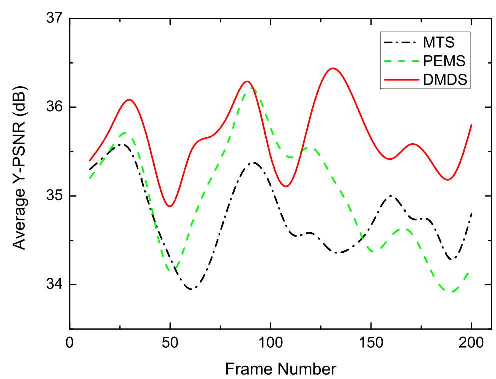
(a) User-1 (Tennis)



(b) User-2 (City)



(c) User-3 (City)



(d) User-4 (Tennis)

Fig. 3. Plots of PSNR versus time for 4 users ($N = 10$, $L = 15$, $N_f = 2$, $N_n = 2$).

we set $T = 300$ms, $P_B = 1\%$, and $\alpha = 350$ unless otherwise specified.

To study the characteristics of the proposed DMDS scheme, we experiment with two different settings, i.e. different network nodes (N), different network links (L), different number of available channels (N_f), and different numbers of network interface (N_n) in each node. The simulation results are presented in Fig.2. It can be observed from Fig.2 that the curves follow an increasing concave trajectory, converging close to the optimum in less than 15 iterations. While the graphs in Fig.2 are for one particular initial condition, we have done simulations for a variety of initial conditions to verify that convergence time is independent of the initial conditions. In addition, it should be noted that, in all experiments, we starts with an initial routing configuration (i.e. the earliest path known by the source) that splits the traffic evenly among the paths for each source-destination pair. For background stream, it is generated according to an on/off source models with exponential distribution of staying time, and average rates between $0 \sim 0.2 \cdot r_l^{in}$ for each link.

To demonstrate the effectiveness of our proposed scheme, DMDS is benchmarked against other two popular scheduling schemes for multi-channel multi-radio wireless networks : i) Maximum Throughput Scheduling (MTS) introduced in [3], in which this scheme seeks for a feasible end-to-end rate allocation vector along with feasible channel assignment to achieve optimal throughput; ii) Provably-Efficient Maximal Scheduling (PEMS) introduced in [2], in which a distributed on-line algorithm is provided to achieve a provable fraction of the maximum system capacity. Fig.3 shows the first 200 frames achieved by four users requesting different video clips under a particular network realization. From Fig.3, we can see that compared to MTS and PEMS schemes, our proposed DMDS scheme has a considerable performance advantages. That is because the above competing schemes only consider the rate maximization or throughput optimum, while our scheme aims at video distortion minimum by joint consider the characteristics of network and video. Note that some of the frame's PSNR values of MTS and PEMS may be higher than that of our proposed DMDS scheme, however without significant performance improvement compared to the video quality of the proposed one. This prove that our proposed scheme is more efficient.

V. CONCLUSIONS

In this paper, we develop fully distributed scheduling schemes that jointly solve the channel-assignment, rate allocation, and routing problems for video streaming over multi-channel multi-radio networks. Importantly, unlike conventional scheduling schemes focus on optimal system throughput or scheduling efficiency, our work aims at achieving minimal video distortion by jointly considering media-aware distribution and network resource allocation. Extensive simulation results are provided which demonstrate the effectiveness of our proposed schemes.

APPENDIX

Proof of Proposition 1: Since (13) is a convex optimization problem satisfying Slater's condition, the duality gap is zero. Therefore, a distributed algorithm for (13) can be derived through the Lagrange dual problem. First we form the following Lagrangian:

$$L(D_{all}, \mathcal{M}, \phi_l) = \sum_s \sum_j D_{all} - \sum_l \phi_l(t)(r_l^{in} - r_l^{out}). \quad (20)$$

However, (20) can not be decoupled yet because ϕ_l refers to many variables. Therefore, I keep on introducing new variable κ_s and additional constraints PTA_l and $\triangle\ R_s^k$:

$$\begin{aligned} L(D_{all}, \mathcal{M}, \phi_l, \kappa_s) &= \sum_s \kappa_s(t) D_{all} - \sum_l \phi_l(t)(r_l^{in} - r_l^{out}) \\ &+ \sum_l \kappa_s(t) \frac{\triangle R_s^k(t)}{PTA_l}. \end{aligned} \quad (21)$$

So far, (21) can be decoupled with three sub-problems as follows:

- Each source s:

$$\max_{F_s} \quad -\sum_{j=1}^{N(s)} \kappa_s(t)(F_{sj})^2 - \sum_{j=1}^{N(s)} F_{sj} \sum_{l=1}^{L} \phi_l(t) M_{sj}^l q_l(t) \quad (22)$$

where $q_l(t)$ is the queue length of link l at time slot t.

- Each link l:

$$\min \quad \sum_l \kappa_s(t) \frac{\triangle R_s^k(t)}{PTA_l} \quad (23)$$

- Each channel c:

$$\min \quad \sum_l \phi_l(t)(r_l^{in} - r_l^{out}) \quad (24)$$

The Lagrangian dual function $L_d(\phi, \kappa)$ is defined as the maximized $L(D_{all}, \mathcal{M}, \phi, \kappa)$ over D_{all} and $\mathcal{M}$ for given ϕ and κ. Each source can compute an optimizer D_{all}^* and each link l and channel c can compute an optimizer $\mathcal{M}^*(\phi, \kappa)$. The Lagrange dual problem of (13) is:

$$\min \quad L_d(\phi_l, \kappa_s) = L(D_{all}^*, \mathcal{M}^*(\phi_l, \kappa_s), \phi_l, \kappa_s) \quad (25)$$

where (ϕ_l, κ_s) are the dual variables. Note that (25) is a convex minimization. Note that, the congestion weight is the basis for channel assignment algorithm, which also serves as a basis for our optimal scheduling scheme. Therefore, we define the iteration method for $u_l^c(t)$ as follows:

$$u_l^c(t+1) = u_l(t+1)/r_l^c(t+1). \quad (26)$$

Since $L_d(\phi_l, \kappa_s)$ may be non-differentiable, an iterative sub-gradient method can be used to update the dual variables to solve (25):

- Queue Length Update:

$$q_l(t+1) = [q_l(t) + \lambda_q(t)\big(\sum_s \sum_j M_{sj}^l F_{sj} R_s^j(t) - \sum_c r_l^c(t)\big)]^+, \quad (27)$$

where $\lambda_q(t)$ represents the queue length step size.

- Rate Increment Update:

$$\triangle R_s^k(t+1) = [\triangle R_s^k(t) + \lambda_R(t)\big(\sum_k \triangle D_{loss}^k - \triangle D_{comp}^k\big)]^+, \quad (28)$$

where $\lambda_R(t)$ represents the rate increment step size.

(27)-(28) are exactly the DMDS scheme steps described in Table.I. Certain choices of step sizes , such as $\lambda_q(t) = \lambda_1/t$, $\lambda_R(t) = \lambda_2/t$ where $\lambda_1 > 0$, $\lambda_2 > 0$, guarantee that this algorithm will converge to the joint optimum. In this case, the convergent point is a globally optimal $\mathcal{M}$ to the problem (13) since we have shown that the problem can be written as convex optimization. ■

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