Scalable Video Coding Based Video Transmission in MRMC Networks: A Cross-Layer Design Perspective

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***Abstract*—In this paper, we discuss the cross-layer network resource allocation scheme for video services in multi-radio multi-channel (MRMC) networks. Since video services include a large amount of traffic to transmit, compared with single-radio single-channel (SRSC) networks, MRMC networks could provide more network resource to support the large video traffic. However, MRMC networks also require more delicate cross-layer resource allocation scheme since more resource is included. In this paper, we consider the scenario that video services are encoded with scalable video coding (SVC), and each one has its own rate demand and quality level requirement. According to the various rate and quality characteristics, we jointly allocate resource in MRMC networks for these video services. We formulate a cross-layer optimization problem with joint consideration of radio assignment, channel allocation, flow routing and time scheduling according to various characteristics of services. The objective is designed as network utility maximization in order to obtain fair resource allocation. Based on the formulation, we compare the performance of the proposed scheme under SRSC networks and MRMC networks. Numerical results show that video services can be served with more resource in MRMC networks and gain higher utility than in SRSC networks. Moreover, we compare the proposed scheme which concerns various characteristics of services with conventional throughput maximization scheme. Simulation results also demonstrate that the proposed scheme performs better than conventional schemes in MRMC networks in terms of network utility.**

***Index Terms*—video transmission, multi-radio multi-channel (MRMC) networks, scalable video coding (SVC).**

I. Introduction

With the development of smart devices, mobile video services become popular in our daily life. Compared with mobile web services, mobile video services have a large amount of traffic data and require more network resource to support video transmission. In parallel with that, IEEE 802.11 standards provide multiple channels in wireless networks. Multi-channel networks can significantly increase throughput by exploiting multiple channels on neighboring links to enable simultaneous transmission. For this reason, the multi-channel network could become a promising option for mobile video communications [1], [2].

As one kind of multi-channel networks, multi-radio multi-channel (MRMC) networks equip each node with multiple radios. Through the multiple radios, a node could transmit over multiple links on multiple channels simultaneously. In MRMC networks, the allocation of introducing radio resource should be jointly considered with other issues, such as channel assignment, flow routing and time scheduling. [3] and [4] discuss the cross-layer resource allocation problem in multi-hop MRMC networks. They jointly study the radio assignment, channel allocation, time scheduling and flow routing problems with the goal of optimizing a fairness factor for each service. [5] designs both distributed and centralized algorithms to minimize the overall network interference in MRMC networks. [6] discusses the cross-layer resource allocation with considering diverse quality-of-service of services. These literatures mainly consider general services in MRMC networks, which may fail to cover some specific characteristics of video communications. Scheduling for video streaming is investigated in single channel wireless networks [7], [8]. However, scheduling video streaming in MRMC networks may be more complicated since more network resource is included. [9] studies the resource allocation problem for video streaming under MRMC networks, where fairness issue and distortion characteristic of video transmission are jointly considered.

With the development of scalable video coding (SVC) [10], [11], a video streaming encoded with SVC consists of a base layer and multiple enhancement layers. The transmission of base layer ensures the basic level of video quality, while when transmission environment is better, more enhancement layers are transmitted and decoded to provide higher temporal and spatial resolution. As a result, a video service, which is encoded with SVC technology, can define its own rate demand and quality level requirement.

This motivates us to design a novel scheme in MRMC networks to allocate resource among video services with different rate and quality requirement based on SVC technology. In this paper, we design a SVC-based video transmission scheme, which could allocate cross-layer network resource according to video services' different rate demand and quality level requirement. Specifically, for video services with large rate demand or high quality demand, more resource will be allocated to support high transmission rate or to transmit more enhancement layers. Besides, we also consider fairness issue by designing a logarithmic function to measure a user's utility. This could avoid the situation that too much resource is allocated to services with high rate and quality demand, while

978-1-4673-2815-9/13/$31.00

services with low rate and quality requirement are ignored. Finally, we consider the single-path flow routing for each video service. The is from the fact that most real-time video services have relatively tight delay constraint. When a packet is divided and transmitted through multiple paths with different delay, to decode it correctly, the receiver may need a relatively long time period to receive all parts of the packet, which may generate unacceptable delay. Our major contributions are summarized as follows:

- We study the SVC-based video transmission in MRMC networks, and conduct cross-layer resource allocation according to video services' rate and quality characteristics. The allocation scheme could match each video service's rate and quality requirement, and thus, improve the resource efficiency.
- We consider a fair resource allocation among services. This ensures that video services with low rate and quality requirement could still access the network and be served well.
- We focus on single-path routing for video services. This is because most of video services have tight delay requirement and multi-path routing may fail to satisfy the delay requirement.
- By carrying out numerical simulations under single-radio single-channel (SRSC) networks and MRMC networks, we demonstrate the benefit of MRMC networks to large data video traffic. Also, by comparing the proposed scheme with the throughput maximization scheme, we show that the proposed scheme with consideration of diversity of video characteristic could exploit the network resource more efficiently.

The rest of this paper is organized as follows. In section II, we describe the network model. In section III, we formulate the resource allocation problem for video streaming based on SVC technology. We present numerical results obtained from computer simulations in section IV. Finally, we conclude this paper in section V.

II. System Model

In Fig. 1, we show a toy topology of an MRMC network with a set of nodes $\mathcal{V} = \{v_1, \ldots, v_n, \ldots, v_{|\mathcal{V}|}\}$ and a set of directed links $\mathcal{E} = \{e_1, \ldots, e_i, \ldots, e_{|\mathcal{E}|}\}$. When e_i is incoming to v_n, we set $\delta_{e_i v_n} = -1$; when e_i is outgoing from v_n, we set $\delta_{e_i v_n} = 1$. I_n represents the number of transceiver radios equipping on node v_n, and $\mathcal{K} = \{1, \ldots, k, \ldots, |\mathcal{K}|\}$ represents the non-overlapping channel set available in this MRMC network. If link e_i works on channel k, the capacity is $C_{e_i}^k$.

In the MRMC network, there is a set of video services $\mathcal{P} = \{1, \ldots, p, \ldots, |\mathcal{P}|\}$. Note that each video service is encoded with SVC. For video service p with source node s_p and termination node t_p, we use d_p and ξ_p to describe its rate demand and quality level. Here, quality level ξ_p indicates that besides the base layer, how many enhancement layers are required by the user of this video. ξ_p is within $[0, 1]$. $\xi_p = 0$ means only base layer transmitted and decoded can satisfy the user of this video; contrarily, $\xi_p = 1$ means a high quality service which requires all enhancement layers on the receiver. For video service p, d_p and ξ_p are predefined and the proposed scheme will allocate resource based on them.

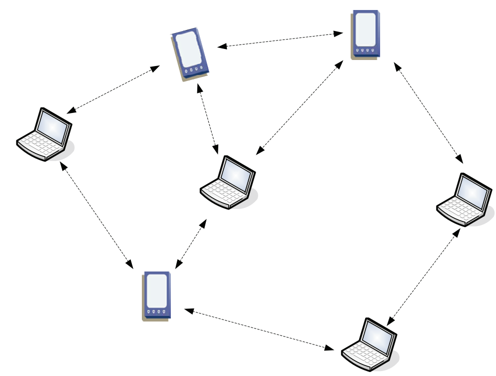

Fig. 1. A toy topology of multi-hop MRMC networks.

Moreover, exploiting the concept of conflict graph in single-channel wireless networks, we derive a corresponding conflict graph of a given MRMC network topology under its single-channel case. The conflict graph can be obtained either in protocol model or physical model [12]. Nodes in this conflict graph represent links in the given MRMC network topology. Edges in this conflict graph represent interference relationship among links in the given MRMC network topology. In this conflict graph, an edge between e_i and e_j means when e_i and e_j are active on a same channel concurrently, they will interfere each other, and we set $\delta_{e_i e_j} = 1$; otherwise, e_i and e_j can work on a same channel without interference, and we set $\delta_{e_i e_j} = 0$. Although we derive the conflict graph based on the single-channel case, in the formulation part, we will delicately design channel allocation and radio assignment scheme under MRMC case to alleviate network interference.

III. Problem Formulation

A. Flow Routing Constraint

Let x_p denote the allocated rate for video service p, and $f_{pe_i}^k$ denote p's flow rate on link e_i over channel k. From network flow theory [13], for each video service p, the source node s_p's outflow rate minus its inflow rate should be equal to the allocated rate x_p. Therefore, at source node s_p, we have

$$x_p = \sum_{e_i \in \mathcal{E}} \sum_{k \in \mathcal{K}} f_{pe_i}^k \delta_{e_i s_p}.$$

where $\delta_{e_i s_p}$ is given by the network topology.

Also, for the termination node t_p of p, x_p is equal to t_p's inflow rate minus its outflow rate, i.e.,

$$-x_p = \sum_{e_i \in \mathcal{E}} \sum_{k \in \mathcal{K}} f_{pe_i}^k \delta_{e_i t_p}.$$

Besides, we use $\mathcal{R}_p = \{r_p^q : r_p^q \in \mathcal{V} \backslash \{s_p, t_p\}\}$ to represent a set of relay nodes for video service p. According to network flow theory, at each relay node r_p^q, the outflow rate minus its inflow rate is 0. That is,

$$0 = \sum_{e_i \in \mathcal{E}} \sum_{k \in \mathcal{K}} f_{pe_i}^k \delta_{e_i r_p^q}.$$

B. Single Path Constraint

In order to analyze flow routing under single-path scenario, we introduce binary variable a_{pe_i} for service p. $a_{pe_i} = 1$ means that e_i is used to transmit p's traffic; otherwise, $a_{pe_i} = 0$.

To find a single path for service p, at most one link of outgoing links of source node s_p is active, i.e.,

$$\sum_{e_i \in \mathcal{E}} \sum_{k \in \mathcal{K}} a_{pe_i} \frac{\delta_{e_i s_p} + 1}{2} \leq 1.$$

Here, $\frac{\delta_{e_i s_p}+1}{2}$ is designed to extract outgoing links of s_p, since $\frac{\delta_{e_i s_p}+1}{2} = 1$ and $\frac{\delta_{e_i s_p}+1}{2} = 0$ if e_i is outgoing and incoming of s_p, respectively.

Similarly, termination node t_p receives traffic from at most one link of its incoming links, which is

$$-\sum_{e_i \in \mathcal{E}} \sum_{k \in \mathcal{K}} a_{pe_i} \frac{\delta_{e_i t_p} - 1}{2} \leq 1,$$

For relay node $r_p^q \in \mathcal{R}_p$, at most one incoming link is used for data receiving, and also, at most one outgoing link is selected for data forward, i.e.,

$$\sum_{e_i \in \mathcal{E}} \sum_{k \in \mathcal{K}} a_{pe_i} \frac{\delta_{e_i r_p^q} + 1}{2} \leq 1.$$

$$-\sum_{e_i \in \mathcal{E}} \sum_{k \in \mathcal{K}} a_{pe_i} \frac{\delta_{e_i r_p^q} - 1}{2} \leq 1.$$

The relationship between a_{pe_i} and $f_{pe_i}^k$ is

$$f_{pe_i}^k \leq C_{e_i}^k a_{pe_i}.$$

C. Link Capacity Constraint

Since we suppose multiple video services can work on one link concurrently, the total flow rate on the link should be less than its link capacity. Thus we write link capacity constraint as follows,

$$\sum_{p \in \mathcal{P}} f_{pe_i}^k \leq C_{e_i}^k.$$

D. Radio Constraint

In MRMC networks, the number of radios equipped on node v_n is I_n. That means node v_n could access to I_n channels simultaneously, and at any time slot, there should be at most I_n active incident links. Here we assume a periodic time scheduling over $\mathcal{T}$ slots. The binary variable $X_{e_i\tau}^k = 1$ denotes e_i is active in slot $\tau \in \mathcal{T}$ on channel k; otherwise $X_{e_i\tau}^k = 0$. Therefore, the radio constraint can be formulated as

$$\sum_{k \in \mathcal{K}} \sum_{e_i \in \mathcal{E}} X_{e_i\tau}^k |\delta_{e_i v_n}| \leq I_n.$$

Since $\sum_{p \in \mathcal{P}} f_{pe_i}^k / C_{e_i}^k = \sum_{\tau \in \mathcal{T}} X_{e_i\tau}^k / |\mathcal{T}|$ in [3], [14], the radio constraint can be rewritten as

$$\sum_{p \in \mathcal{P}} \sum_{e_i \in \mathcal{E}} \sum_{k \in \mathcal{K}} \frac{f_{pe_i}^k |\delta_{e_i v_n}|}{C_{e_i}^k} \leq I_n.$$

E. Time Scheduling Constraint

From [3], [14], for each link-channel pair (e_i, k), the time scheduling constraint is

$$\sum_{p \in \mathcal{P}} \frac{f_{pe_i}^k}{C_{e_i}^k} + \sum_{p \in \mathcal{P}} \sum_{e_j \in \mathcal{E}} \frac{f_{pe_j}^k \delta_{e_i e_j}}{C_{e_j}^k} \leq 1.$$

This constraint ensures that when link-channel pair (e_i, k) is active, all interfering link-channel pairs $\{(e_j, k) : e_j \in \mathcal{E}, \delta_{e_i e_j} = 1\}$ are inactive. In this way, the interference-free time scheduling is effectively ensured.

F. Objective Function

We define $U_p(x_p)$ as the utility function of video service p, which indicates the degree of satisfactory of p. According to [15], $U_p(x_p)$ is given as follows,

$$U(x_p) = \begin{cases} w_p \log x_p, & \alpha = 1 \\ w_p \frac{x_p^{1-\alpha}}{1-\alpha}, & \alpha \neq 1, \end{cases}$$

where weight $w_p > 0$. $\alpha = 0$ provides network throughput maximization, but may generate unfair resource allocation. $\alpha \to \infty$ provides max-min fairness allocation. While $\alpha = 1$ gives proportional fairness allocation [16]. In this paper, we set $U(x_p) = w_p \log x_p$ as the utility function of video service p to converge a proportionally fair resource allocation. Meanwhile, we fix $w_p = d_p \xi_p$, which means weight w_p is determined by video service p's rate demand and quality requirement. This is reasonable since video services either with a large amount of rate demand or with high resolution requirement should be allocated more resource. Moreover, by considering proportional fairness, both high-weight and low-weight video services can be allocated certain amount of resource and served well in networks with limited resource.

The objective function in this paper is to maximize the network utility, i.e., the summation of utilities over all services.

G. Problem Modeling

From expression above, we formulate the cross-layer resource allocation problem in MRMC networks for video services as follows,

$$\max \sum_{p \in \mathcal{P}} d_p \xi_p \log x_p \tag{1}$$

subject to:

$$x_p \leq \sum_{e_i \in \mathcal{E}} \sum_{k \in \mathcal{K}} f_{pe_i}^k \delta_{e_i s_p} \qquad (p \in \mathcal{P}) \tag{1a}$$

$$-x_p \leq \sum_{e_i \in \mathcal{E}} \sum_{k \in \mathcal{K}} f_{pe_i}^k \delta_{e_i t_p} \qquad (p \in \mathcal{P}) \tag{1b}$$

$$0 \leq \sum_{e_i \in \mathcal{E}} \sum_{k \in \mathcal{K}} f_{pe_i}^k \delta_{e_i r_p^q} \qquad (p \in \mathcal{P} \text{ and } r_p^q \in \mathcal{R}_p) \tag{1c}$$

$$\sum_{e_i \in \mathcal{E}} \sum_{k \in \mathcal{K}} a_{pe_i} \frac{\delta_{e_i s_p} + 1}{2} \leq 1 \quad (p \in \mathcal{P}) \tag{1d}$$

$$-\sum_{e_i \in \mathcal{E}} \sum_{k \in \mathcal{K}} a_{pe_i} \frac{\delta_{e_i t_p} - 1}{2} \leq 1 \quad (p \in \mathcal{P}) \tag{1e}$$

$$\sum_{e_i \in \mathcal{E}} \sum_{k \in \mathcal{K}} a_{pe_i} \frac{\delta_{e_i r_p^q} + 1}{2} \leq 1 \quad (p \in \mathcal{P} \text{ and } r_p^q \in \mathcal{R}_p) \tag{1f}$$

$$-\sum_{e_i \in \mathcal{E}} \sum_{k \in \mathcal{K}} a_{pe_i} \frac{\delta_{e_i r_p^q} - 1}{2} \leq 1 \quad (p \in \mathcal{P} \text{ and } r_p^q \in \mathcal{R}_p) \tag{1g}$$

$$f_{pe_i}^k \leq C_{e_i}^k a_{pe_i} \quad (e_i \in \mathcal{E} \;\; k \in \mathcal{K} \text{ and } p \in \mathcal{P}) \tag{1h}$$

$$\sum_{p \in \mathcal{P}} f_{pe_i}^k \leq C_{e_i}^k \quad (e_i \in \mathcal{E} \text{ and } k \in \mathcal{K}) \tag{1i}$$

$$\sum_{p \in \mathcal{P}} \sum_{e_i \in \mathcal{E}} \sum_{k \in \mathcal{K}} \frac{f_{pe_i}^k |\delta_{e_i v_n}|}{C_{e_i}^k} \leq I \quad (v_n \in \mathcal{V}) \tag{1j}$$

$$\sum_{p \in \mathcal{P}} \frac{f_{pe_i}^k}{C_{e_i}^k} + \sum_{p \in \mathcal{P}} \sum_{e_j \in \mathcal{E}} \frac{f_{pe_j}^k \delta_{e_i e_j}}{C_{e_j}^k} \leq 1 \;\; (e_i \in \mathcal{E} \text{ and } k \in \mathcal{K}) \tag{1k}$$

$$0 \leq f_{pe_i}^k \quad (p \in \mathcal{P}, \;\; e_i \in \mathcal{E} \text{ and } k \in \mathcal{K}) \tag{1l}$$

$$0 \leq x_p \quad (p \in \mathcal{P}) \tag{1m}$$

$$a_{pe_i} \in \{0, 1\} \quad (p \in \mathcal{P}, \;\; e_i \in \mathcal{E} \text{ and } k \in \mathcal{K}). \tag{1n}$$

where $\delta_{e_i s_p}$, $\delta_{e_i t_p}$, $\delta_{e_i r_p^q}$, d_p, ξ_p, $C_{e_i}^k$, $\delta_{e_i e_j}$ and $\delta_{e_i v_n}$ are given by the pre-generated network topology and video services, and $f_{pe_i}^k$, a_{pe_i} and x_p are optimization variables.

In this formulation, (1a)-(1c) are flow routing constraints. (1d)-(1h) are single path constraints. (1i) is link capacity constraint. (1j) is radio constraint on each node. (1k) is interference-free time scheduling constraint. (1l)-(1m) specify that all $f_{pe_i}^k$ and x_p are positive. (1n) indicates that all a_{pe_i} are binary. Besides, in (1a)-(1c), we use inequalities instead of equalities to facilitate the solving process without changing the optimal solution [17], [18].

Since a_{pe_i} is binary, the formulation becomes a mixed-integer linear programming (MILP) problem. Although the problem is NP-hard, it can be solved by softwares (e.g., CPLEX) or some typical algorithms (e.g., branch and bound) [19], [20].

IV. Numerical Results and Performance Analysis

In this section, we compare the performance of the proposed scheme (SVC-based scheme) with the conventional throughput maximization scheme [21] in a random MRMC topology in Fig. 2 and Fig. 3. Besides, to evaluate the benefit of MRMC networks to large video traffic services, we compare the network utility under SRSC networks and MRMC networks in Table I. Here the conventional throughput maximization scheme optimizes the linear summation of all video services' throughput, which does not concern the SVC technology, and also ignores the rate and quality characteristics of video services.

The MRMC network is randomly generated with 20 nodes, which are located in an area of $1000m \times 1000m$. We set transmission range and interference range as $250m$ and $500m$, respectively. The link capacity over each channel is selected from $1Mbps$, $2Mbps$, $5.5Mbps$, and $11Mbps$, randomly. There are four video services in the MRMC network, each of which is assumed encoded by SVC. Each service has a rate-quality pair, (d_p, ξ_p), where d_p and ξ_p are both randomly chosen within $[0, 1]$. In Fig. 2, we fix radio number for each node as 2, and change the number of available channels from 2 to 5. Similarly, in Fig. 3, we set the channel number as 5, and change the radio number of each node from 1 to 5. In the MRMC network of Table I, we set the channel number as 3 and radio number as 3.

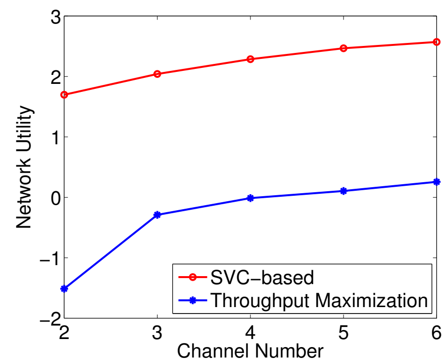

Fig. 2. Performance comparison of the proposed SVC-based scheme and Throughput maximization scheme. Radio number is 2, Channel number changes from 2 to 6.

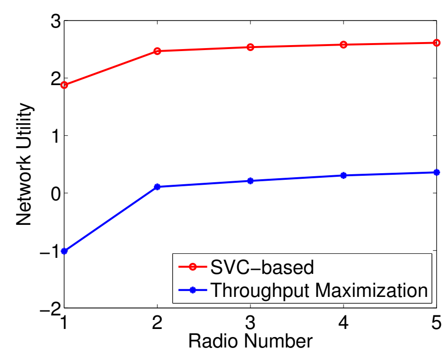

Fig. 3. Performance comparison of the proposed SVC-based scheme and Throughput maximization scheme. Channel number is 5, Radio number changes from 1 to 5.

TABLE I
PERFORMANCE COMPARISON BETWEEN SRSC NETWORKS AND MRMC NETWORKS.

	SVC-based Scheme	Throughput Maximization Scheme
SRSC	1.0039	-1.8936
MRMC	2.1025	-0.0557

From the numerical results of Fig. 2, Fig. 3 and Table I, there are three observations can be made in order. First, in Fig. 2 and Fig. 3, the network utility under both schemes increases with the increase of network resource (e.g., channel number and radio number). However, the utility improvement is becoming slow down with the increase of resource. The observation is accordance with simulation results in [3], and it gives us a guideline to set the appropriate number of channels and radios in an MRMC network. Second, in Fig. 2 and Fig. 3, the proposed SVC-based scheme performs better than the throughput maximization scheme in terms of network utility. This is because for video services encoded with SVC, the proposed SVC-based scheme considers the diverse of rate and quality characteristics of video services, and thus, allocates resource efficiently with this consideration. However, the throughput maximization scheme ignores the characteristics of services and may fail to satisfy all services well. Third, in Table I, the network utility in MRMC networks is larger than that in SRSC networks. Since MRMC networks could provide more network resource than SRSC networks, MRMC networks are more beneficial for video communications which has large traffic data to transmit.

V. Conclusion

In this paper, we have studied the resource allocation problem in MRMC networks for video services. Under SVC technology, we consider the diversity of video services' rate and quality requirement, and conduct resource allocation with this consideration. We have formulated the problem by jointly optimize the radio assignment, channel allocation, flow routing and time scheduling. In the formulation, the goal is to optimize the network utility, which is weighted by the product of each service's rate demand and quality level requirement. Based on the formulation, we have evaluated the performance of the proposed scheme in SRSC and MRMC networks. Numerical results have shown that MRMC networks provide higher utility for video services since more network resource is available in MRMC networks. Also, we have compared the performance of the proposed scheme with throughput maximization in terms of network utility. The comparison indicates that the proposed scheme could exploit network resource more efficiently by considering the diversity of video services' characteristics.

Acknowledgement

This work was partially supported by the NSFC under grant 61231008, National S&T Major Project under grant 2011ZX03005- 004, 2011ZX03004-003, 2011ZX03005-003-03 and 2013ZX03004007-003, Shaanxi 13115 Project under grant 2010ZDKG-26, National Basic Research Program of China under grant 2009CB320404, Program for Changjiang Scholars and Innovative Research Team in University under grant IRT0852, 111 Project under grant B08038, and State Key Laboratory Foundation under grant ISN 1002005 and ISN090305. The work of P. Li was partially supported by the US National Science Foundation under grant CNS-1149786. The work of M. Pan was partially supported by the U.S. National Science Foundation under grant NSF-1137732.

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