Dynamic Rate Allocation and Opportunistic Routing for Scalable Video Multirate Multicast over Time-Varying Wireless Networks

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***Abstract*—In this paper, we consider the time-varying characteristics of practical wireless networks, and propose a joint dynamic rate allocation and transmission scheduling optimization scheme for scalable video multi-rate multicast based on opportunistic routing (OR) and network coding. With OR, the decision of optimal routes for scalable video coding (SVC) layered streaming is integrated into the joint optimization formulation. The network throughput is also increased by taking advantage of the broadcast nature of the wireless shared medium and by network coding operations in intermediate nodes. To maximize the overall video reception quality among all destinations, the proposed scheme can jointly optimize the video reception rate, the associated routes to different destinations, and the time fraction scheduling of transmitter sets that are concurrently transmitting in the shared wireless medium. By using dual decomposition and primal-dual update approach, we develop a cross-layer algorithm in a fully distributed manner. Simulation results demonstrate significant network multicast throughput improvement and adaptation to dynamic network changes relative to existing optimization schemes.**

***Index Terms*—Scalable video coding, multi-rate multicast, dynamic rate allocation, opportunistic routing, network coding.**

I. Introduction

Wireless video has experienced extensive growth in the last decades and been utilized for a wide range of applications. Multi-rate multicast for scalable video streams, as an important method for video content distribution, can benefit the overall network utility by adapting to different user requirements and heterogeneous network conditions [1]. A scalable video coding (SVC) stream comprising a base layer and several enhancement layers with a flexible multi-dimension layer structure, provides various operating points in spatial resolution, temporal frame rate, and video reconstruction quality. Multi-rate multicast allows different layers to be delivered in different multicast groups and subscribed by heterogeneous receivers with different computation/communication resources and capabilities.

Traditional optimization based rate control schemes for multi-rate multicast in general networks have been proposed in literature [2], and often formulated as a network utility maximization (NUM) problem with distributed implementation that maximizes the total receiver utility for all multi-rate multicast sessions. As multi-rate multicast applications for SVC, several resource rate and network flow control schemes [3], [4] adopted video reception quality as destination's utility and attempted to maximize the overall video reception quality for all destinations and all SVC video layers, while satisfying SVC layer dependency and network capacity constraints.

These schemes, though proved to have optimal (near optimal) performance, suffer from two limitations. First, they are based on the assumption that network characteristics (e.g., topology, link capacity, etc.) are static and do not change over time. Second, one or multiple routes between each source-destination pair have to be predefined before the optimization scheme operates. In practical wireless networks, however, these two assumptions would lead to infeasible or poor performance since the wireless channel is time-varying by nature, and the associated wireless channel state changes over time frequently. Therefore, the scalable video multi-rate multicast problems over time-varying wireless networks are still technical challenges that require further investigation to capture the temporal dynamics in practice. To this end, the distributed robust algorithm in [4] was proposed to enhance the robustness of NUM formulation by reserving partial bandwidth for several backup paths and by introducing the fluctuation range of channel capacity. To obtain a tradeoff between optimization performance and robustness, however, it has to sacrifice network throughput to be protected from infeasible solution caused by dynamic network changes.

In order to efficiently cope with time-varying wireless channels and imperative needs for dynamic routing, opportunistic routing (OR) approaches have been proposed and investigated in [5]- [7], to exploit the broadcast nature and the spatial diversity of the wireless shared medium. OR works in such a way that one wireless transmission originated from a transmitter can be overheard by a set of forwarding candidates within its effective transmission range, and only one actual relay node will be selected for packet forwarding according to its relay priority. In comparison with traditional routing which specifies only one forwarding candidate for a transmitter, involving multiple forwarding candidates by OR could combine multiple weak links into one strong link, and increase the probability of at least one next-hop node having successfully received the packets. Such increase of packet forwarding success probability within one wireless transmission decreases the probability for retransmission, which in turn enhances the network throughput [5], [6]. Zeng *et al.* in [7] proved that with OR, the end-to-end throughput can be significantly improved in multi-rate and multi-hop wireless networks compared to the traditional routing. Another advantage of OR is that the routes for a packet between any source-destination pair are not required to

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be specified in advance. On the contrary, the next-hop forwarder is determined for a packet at the transmitter node on the fly based on OR strategy, and thus the route is also dynamic. However, the existing work on OR mainly focused on the end-to-end throughput bound and performance limit of unicast, and little work has been done to study the scheme and network throughput of opportunistic multicast routing.

To address the above issues, in this paper, we focus on scalable video multi-rate multicast problem over practical wireless networks. The main contribution is as follows. First, we adopt the multi-period formulation of dynamic network utility maximization to formulate a joint dynamic rate allocation and transmission scheduling optimization formulation for scalable video multi-rate multicast based on OR and network coding. In accordance with time-varying channel states, the received rates of destination nodes are coupled across time by SVC encoding/decoding and layer dependency constraints. Second, different from existing SVC multi-rate multicast schemes with predefined routes, the decision of optimal routes for each destination node subscribing to different SVC layers is integrated into the proposed joint optimization formulation by OR. Third, the network throughput of opportunistic multicast routing is studied and achieved by the proposed cross-layer algorithm, in the form of maximum total video reception rate of all destinations. Fourth, with the wireless link dynamics either known or predicted, the proposed scheme can jointly optimize the video reception rate, the associated routes to destinations, and the time fraction scheduling of transmitter sets that are concurrently transmitting in the shared wireless medium. Simulation results show that significant network multicast throughput improvement and adaptation to dynamic network changes can be achieved compared to existing schemes.

The rest of this paper is organized as follows. In Section II, we introduce network models, and formulate the OR based dynamic rate allocation and transmission scheduling problem. Section III develops a distributed cross-layer algorithm. Simulation results are shown and analyzed in Section IV. Section V concludes this paper.

II. Dynamic Rate Allocation and Transmission Scheduling Based on Opportunistic Routing

A. Wireless Network Under Time-Varying Channels

Consider the scalable video streaming over a wireless network with all wireless nodes randomly placed on a plane. We model such wireless network as a directed graph $G = (V, E)$, where V is the set of wireless nodes and E is the set of wireless links. Alternatively, the node set V can be viewed as the union of three subsets, i.e., $V = \{s\} \cup N \cup D$, where s, N and D represent the single video source node, the set of relay nodes, and the set of destination nodes, respectively.

In a practical wireless network, the channel state between two nodes might frequently change (e.g., link failures or link fluctuations) due to node mobility and wireless channel fading [8]. In accordance with the time-varying characteristics of wireless links, we assume that within the entire period of scalable video streaming, time is slotted with slots normalized to integral units $t \in \{0, 1, 2, \dots T\}$, and channels hold their states within the duration of a time slot [9]. At time slot t, each node i ($i \in N$) can broadcast data packets to its neighboring nodes with capacity C_i. Denote $p_{(i,j)}(t)$ as the packet reception ratio (PRR) from transmitting node i to receiving node j through link $l = (i, j)$, then a directed link (i, j) exists if and only if $p_{(i,j)}(t)$ is larger than a positive PRR threshold p_{td} [7]. Alternatively, let $dist_{(i,j)}$ denote the Euclidean distance between nodes i and j, then there is a usable directed link (i, j) when $dist_{(i,j)} < D_t$, where the effective transmission range D_t is defined as the maximum allowable sender-receiver distance at which the PRR equals to the threshold p_{td}.

B. Scalable Video Coding and Rate-Distortion Model

Assume an SVC source video stream encoded with a set of M layers $\{L_1, L_2, \dots, L_M\}$. The transmission of each layer corresponds to a multicast session m through the network. The SVC multicast layers are supposed to be subscribed by a destination in an incremental order, since layer $m+1$ is only decodable with the existence of all the previous layers 1 to m. Also, we introduce a tolerable rate region $[r^m_{\min}, r^m_{\max}]$ and suppose that each layer m is distributed over a multicast session at a variable transmission rate chosen from that rate region. Let $R^{md}(t)$ represent the received rate by destination node d for video layer m at time slot t, then, according to [4], the SVC encoding/decoding constraint is proposed as follows:

$$\left[\sum_{t=1}^{T} R^{md}(t)\cdot\Delta T\right]\cdot\left[\sum_{t=1}^{T} R^{md}(t)\cdot\Delta T - r^m_{\min}\cdot T\cdot\Delta T\right] \cdot\left[\sum_{t=1}^{T} R^{md}(t)\cdot\Delta T - r^m_{\max}\cdot T\cdot\Delta T\right] \le 0,\ \forall m, d \quad (1)$$

where ΔT denotes the duration of a time slot. Since $R^{md}(t)$ is nonnegative, constraint (1) indicates that a video layer is either not subscribed with zero rate, or received by a destination node with a sufficient amount of information for that video layer. Together with constraint (1), the aforementioned SVC layer dependency constraint is promised and given by:

$$\frac{\sum_{t=1}^{T} R^{(m+1)d}(t)}{r^{(m+1)}_{\max}\cdot T} \le \frac{\sum_{t=1}^{T} R^{md}(t)}{r^m_{\min}\cdot T},\ \forall m, d \quad (2)$$

From the perspective of application-layer QoS, to accurately measure the satisfaction perceived by a destination node, the following rate-distortion (RD) model in [10] is adopted as the utility for video applications:

$$D_e(R_e) = \frac{\theta}{R_e - R_0} + D_0 \quad (3)$$

where D_e is the distortion of the encoded video sequence and R_e is the encoding rate. The remaining variables, θ, R_0 and D_0, are the parameters of the RD model, which depend on the actual video content and are estimated from empirical rate distortion curves using regression techniques.

At time slot t, we associate with $R^{md}(t)$ a strictly increasing, differentiable and concave utility function $U(R^{md}(t))$. Within the context of SVC, this utility function is defined as the QoS improvement in the form of distortion decrement when destination node d successfully receives and decodes layer m:

$$U(R^{md}(t)) = -\left[D_e\left(\sum_{k=1}^{m} R^{kd}(t)\right) - D_e\left(\sum_{k=1}^{m-1} R^{kd}(t)\right)\right] \quad (4)$$

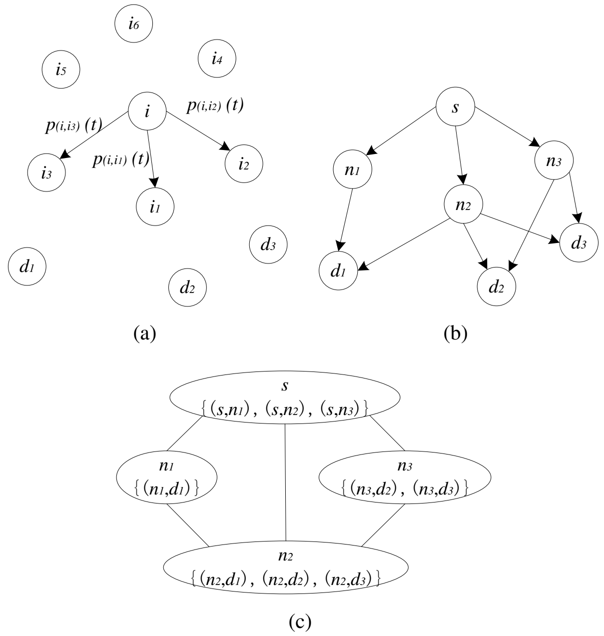


Fig. 1. (a) Basic module of OR, where at time slot t node i is forwarding a packet to destination node $d_1 \sim d_3$ with forwarding candidate set $F_i(t) = \{i_1, i_2, i_3\}$; (b) original network topology graph; and (c) transmitter conflict graph according to OR.

C. Opportunistic Routing and Scheduling

1) OR: Illustrated in Fig. 1(a) is the basic module of OR. Suppose that at time slot t, node i is forwarding a packet to destination nodes $d_1 \sim d_3$. A set $F_i(t) = \{i_1, i_2, \ldots, i_r\}$ including r nodes is chosen as the forwarding candidate set to participate in the local opportunistic forwarding based on a specific selection strategy, e.g., the neighboring nodes that are geographically closer to the destination node than node i are selected. Also, $F_i(t)$ is an ordered set with $i_1 > i_2 > \cdots > i_r$. OR works by node i forwarding the packet to the nodes within $F_i(t)$. Whenever the nodes in the forwarding candidate set receive the packet broadcasted by node i, one of them will continue forwarding the received packet in accordance with their relay priority, which is indicated by the order of the elements in $F_i(t)$. As shown in Fig. 1(a), $F_i(t) = \{i_1, i_2, i_3\}$, where the order of nodes depends on the overall closeness of their Euclidean distance to all destination nodes. A forwarding candidate node will forward the packet sending from node i only when all nodes in $F_i(t)$ with higher priorities fail the forwarding task. Such forwarding operation will iterate until the packet reaches the destination node through a specific route.

Without loss of generality, we adopt geographic OR scheme [6] as the forwarder candidate set selection and prioritization scheme, and assume that each node knows the location information of itself, its one-hop neighbors, and the destination nodes. For a transmitter that is broadcasting a packet, the forwarding candidate set is formed by its neighbors that are geographically closer to the destinations. Within the forwarding candidate set, the nodes with closer total distance to all destination nodes should be assigned with higher relay priorities.

2) Transmitter Conflict and Concurrent Transmitter Sets: The throughput of a wireless link is interrelated and affected by adjacent links because of link contention and interference in the shared transmission medium. Considering the broadcast nature in OR, we extend from the protocol model for link conflict [11] and further define the transmitter conflict as two or more transmitters that cannot be transmitting simultaneously due to the conflict among links to their associated forwarding candidates. To better understand the conflict relationship between transmitters and their associated forwarding candidates for OR, we construct an illustrative transmitter conflict graph in Fig. 1(c), with the original network topology shown in Fig. 1(b). Suppose that source node s is multicasting SVC packets to three destination nodes $d_1 \sim d_3$, via three relay nodes $n_1 \sim n_3$. With OR, nodes s, n_1, n_2 and n_3 can be selected as transmitters or forwarders, however, they cannot be forwarding packets simultaneously because of the transmitter conflict. In the transmitter conflict graph, each vertex denotes a transmitter in the original network topology associated with a set of links to its forwarding candidates. The conflict of two transmitters exists if they cannot be transmitting at the same time due to the conflict among their associated links, and is accordingly represented as an edge between two vertices in the transmitter conflict graph.

To characterize the impact of wireless interference and the opportunistic nature of OR, in the following, we introduce the concepts of concurrent transmitter set (CTS) as defined in [7]. A CTS is defined as a set of transmitters, when all nodes within that set are transmitting packets at the same time, all the links associated with them to their forwarding candidates can make successful transmissions. The basic idea of CTS is to avoid transmitter conflict by requiring all the opportunistic receivers to be interference-free at the same time. In order to make full use of the wireless shared medium and achieve the capacity bound of the network, a maximum CTS is defined as a CTS, if adding any one more node into it will lead to a non-CTS. For illustration, according to Fig. 1(c), all the possible maximum CTSs can be obtained as $\{s\}$, $\{n_2\}$ and $\{n_1, n_3\}$.

3) Effective Transmission Rate and Maximum CTS Scheduling: In a specific maximum CTS, all the transmitters can deliver packets via their associated links to the corresponding forwarder candidates. Here, according to the OR strategy, we define the concepts of effective transmission rate of links associated with a transmitter in a maximum CTS. Denote an indicator function $\psi_i^\alpha(t)$ to represent the relationship between node i and a particular maximum CTS $\Gamma^\alpha(t)$. Specifically, $\psi_i^\alpha(t) = 1$ if node i is in maximum CTS $\Gamma^\alpha(t)$ within time slot t, and $\psi_i^\alpha(t) = 0$ otherwise. Based on OR, a forwarding candidate might have the chance to forward the packet only when it receives the packet successfully and all the candidates with higher relay priorities fail to do so. Therefore, at time slot t, for any forwarder candidate $i_q \in F_i(t)$, the effective transmission rate of link (i, i_q) in maximum CTS $\Gamma^\alpha(t)$ is derived as:

$$C^\alpha_{(i,i_q)}(t) = \psi_i^\alpha(t) \cdot C_i \cdot p_{(i,i_q)}(t) \prod_{k=0}^{q-1} (1 - p_{(i,i_k)}(t)) \qquad (5)$$

where C_i is the broadcast capacity of node i, $p_{(i,i_0)}(t) := 0$ is a zero constant for the consistency of (5) when $i_q = i_1$, $p_{(i,i_q)}(t) \prod_{k=0}^{q-1}(1 - p_{(i,k)}(t))$ represents the probability of node i_q correctly receiving the packet while all higher-order candidates $i_1, i_2, \ldots, i_{q-1}$ have experienced packet reception failure.

Let $\{\Gamma^1(t), \Gamma^2(t), \ldots, \Gamma^A(t)\}$ denote the set of all the maximum CTSs in the wireless network at time slot t. Due to the transmitter conflict, at any time within that time slot, no more than one CTS can be scheduled to transmit while all the transmitters in that CTS can forward packets simultaneously. Set $\lambda^{\alpha}(t)$ as the fraction of time scheduled to a specific maximum CTS $\Gamma^{\alpha}(t)$, then, we can have an OR based scheduling problem that aims to achieve the maximum network utility by optimally scheduling the transmission of all the maximum CTSs. Furthermore, let $f^{m}_{(i,j)}(t)$ denote the actual physical flow of SVC layer m on link (i,j), thus the constraints for the maximum CTS scheduling are given as follows:

$$\sum_{\alpha=1}^{A} \lambda^{\alpha}(t) \leq 1, \ \forall t \tag{6}$$

$$\sum_{m=1}^{M} f^{m}_{(i,j)}(t) \leq \sum_{\alpha=1}^{A} \lambda^{\alpha}(t) \cdot C^{\alpha}_{(i,j)}(t), \ \forall t, (i,j) \tag{7}$$

where constraint (6) ensures that no more than one maximum CTS is scheduled to transmit at any time within time slot t, and constraint (7) specifies that the actual physical flow of all SVC sessions delivered on a link should not exceed the total amount of flow that can be supported by all activity periods of the maximum CTSs.

D. Network Coding

By utilizing network coding, relay nodes are allowed to perform algebraic operations on the received packets to facilitate efficient information delivery over networks [2], [12]. Here, we adopt intra-session network coding as in [12] and only allow data packets from the same layer to be combined. Defining $g^{md}_{(i,j)}(t)$ as the virtual information flow rate for destination node d within multicast session m at time slot t, we have the following information flow conservation condition:

$$\sum_{j:(i,j)\in E} g^{md}_{(i,j)}(t) - \sum_{j:(j,i)\in E} g^{md}_{(j,i)}(t) = \sigma^{md}_{i}(t), \ \forall i, m, d, t \tag{8}$$

$$\sigma^{md}_{i}(t) = \begin{cases} R^{md}(t), & \text{for } i = s \\ -R^{md}(t), & \text{for } i = d \\ 0, & \text{otherwise} \end{cases}, \ \forall i, m, d, t \tag{9}$$

By being coded together, flows to different destinations of a specific SVC video layer are able to share the network capacity. Such flow sharing property requires the actual physical flow on each link to be the maximum of the individual destinations' virtual information flows, i.e.,

$$g^{md}_{(i,j)}(t) \leq f^{m}_{(i,j)}(t), \ \forall (i,j), m, d, t \tag{10}$$

E. Problem Formulation

Previous work on scalable video multicast is mainly based on static network assumption and predetermined routes between source-destinations, and thus fails to capture the temporal dynamics in practical networks. In practice, however, the mobility of wireless nodes (e.g., node arrival, departure, or movement) would often occur. Thus the channel state information of a wireless link varies over time. In this work, the SVC multicast problem is required to be adapted to link (i,j)'s time-varying packet reception ratio $p_{(i,j)}(t)$, which is dynamic with regard to time slots and assumed to be known for all time slots. And the decision of optimal routes for each destination subscribing to different SVC layers is integrated by opportunistic multicast routing. In such scalable video multi-rate multicast applications, a certain amount of information for each multicast session m has to be delivered to destination nodes within the transmission period, in order to meet the SVC decoding requirement. Accordingly, we adopt the multi-period formulation of dynamic network utility maximization to formulate a joint dynamic rate allocation and transmission scheduling optimization problem based on opportunistic multicast routing, where the received rates by destination nodes are coupled across time by SVC encoding/decoding constraints. The proposed opportunistic multicast routing formulation for SVC streaming is as follows:

$$\textbf{P1:} \quad \max_{\mathbf{R},\mathbf{g},\mathbf{f},\boldsymbol{\lambda}\succeq\mathbf{0}} \sum_{t=1}^{T} \sum_{d\in D} \sum_{m=1}^{M} U(R^{md}(t)) \tag{11}$$

s.t. Constraints (1), (2), (6), (7), (8), and (10)

In **P1**, the objective is to achieve the maximum total utility of the SVC layers received by all recipients, by jointly optimizing the video reception rate $\mathbf{R}$, the routes to destination nodes with associated virtual information flow $\boldsymbol{g}$ and physical flow $\boldsymbol{f}$, and the time fraction of maximum CTSs $\boldsymbol{\lambda}$.

F. Stochastic Dynamic Problem

As above formulation, we assume that the dynamic packet reception ratios for each link are known a priori for all time slots. In some applications when links' PRRs are not known in advance, according to [13], we can model such time-varying behavior of a wireless channel at link (i,j) as an ergodic finite-state Markov chain (FSMC), with H different packet reception ratios (denoted by vector $\mathbf{P}_{(i,j)} = (P^{1}_{(i,j)}, \ldots, P^{h}_{(i,j)}, \ldots, P^{H}_{(i,j)})^{T}$) corresponding to a finite set of H states, and a transition probability matrix $\mathbf{Tr}_{(i,j)} \in \mathbb{R}^{H\times H}_{+}$ which has the following structure:

$$\mathbf{Tr}_{(i,j)} = \begin{pmatrix} \omega & \varepsilon & 0 & 0 & 0 & \ldots & 0 & \varepsilon \\ \varepsilon & \omega & \varepsilon & 0 & 0 & \ldots & 0 & 0 \\ 0 & \varepsilon & \omega & \varepsilon & 0 & \ldots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ \varepsilon & 0 & 0 & 0 & 0 & \ldots & \varepsilon & \omega \end{pmatrix} \tag{12}$$

where $\omega = 1 - 2\varepsilon$ and $\varepsilon = \mathbb{O}(f_d\Delta)$, f_d and Δ are the doppler frequency shift and symbol duration, respectively. Suppose that at time slot t, we have observed the state of link (i,j) with associated PRR, as $p_{(i,j)}(t) = P^{h}_{(i,j)}$. Based on the transition probability that is independent of time slot, the expected value of future PRRs can be predicted by the h-th row of τ-th power of $\mathbf{Tr}_{(i,j)}$:

$$\hat{p}_{(i,j)}(t+\tau|t) = [\mathbf{Tr}^{(\tau)}_{(i,j)}]_{(h)} \cdot \mathbf{P}_{(i,j)}, \quad \tau = 1, 2, \ldots, T-t \tag{13}$$

In this way, the future channel state information can be predicted for wireless links based on current observation, and plugged into **P1** to form a stochastic dynamic version of **P1**.

III. Distributed Cross-layer Algorithm

For distributive implementation, decomposition methods (primal or dual decomposition) are commonly used [14] to decompose a large optimization problem into a set of small subproblems, which can be solved by distributed and often iterative algorithm converging to the global optimum. With dual decomposition, problem **P1** can be decoupled by relaxing all the coupling constraints (1), (2), (6), (7), (8), and (10), with respect to Lagrange multiplier vector $\boldsymbol{\vartheta} = (\gamma, \nu, \theta, \beta, \mu, \eta)$. Let $L(\mathbf{R}, \mathbf{g}, \mathbf{f}, \boldsymbol{\lambda}, \boldsymbol{\vartheta})$ denote the Lagrangian of **P1**, the Lagrange dual function is then given by:

$$g(\boldsymbol{\vartheta}) = \sup_{\mathbf{R},\mathbf{g},\mathbf{f},\boldsymbol{\lambda}\succeq \mathbf{0}} L(\mathbf{R}, \mathbf{g}, \mathbf{f}, \boldsymbol{\lambda}, \boldsymbol{\vartheta}) \tag{14}$$

And the Lagrange dual problem of **P1** is expressed as:

$$\min_{\eta,\theta,\beta,\gamma,\nu\succeq \mathbf{0}} g(\boldsymbol{\vartheta}) \tag{15}$$

Optimization theory [14] ensures that the convex constrained optimization problem **P1** is equivalent to its Lagrange dual problem in Eq. (15), and thus can be decomposed into a master dual problem in Eq. (15) with several cross-layer sub-problems of transport, network, and link layers, with regard to primal variables $\mathbf{R}$, $\mathbf{g}$, $\mathbf{f}$, and $\boldsymbol{\lambda}$, respectively. Based on the primal-dual algorithm that simultaneously updates primal and dual variables, the distributive cross-layer iteration algorithm is developed as follows, where subscript k denotes the iteration index, $\boldsymbol{\delta}$ is positive stepsize, and $[\cdot]^+$ represents the projection onto $\mathbb{R}_+$.

1) Rate Control:

$$\begin{aligned} R^{md}(t)|_{k+1} = \Bigg[R^{md}(t) + \delta^{(R)}\Bigg(U'(R^{md}(t)) + \mu_s^{md}(t) \\ - \mu_d^{md}(t) - \frac{\nu^{(m-1)d}}{r_{\max}^m} + \frac{\nu^{md}}{r_{\min}^m} - \gamma^{md}(t)\{3[\sum_{t=1}^{T} R^{md}(t)]^2 \\ - 2T(r_{\min}^m + r_{\max}^m)[\sum_{t=1}^{T} R^{md}(t)] + T^2 r_{\min}^m r_{\max}^m\}\Bigg)\Bigg]_k^+ \end{aligned}$$

2) Link Flow Control and Routing:

$$g_{(i,j)}^{md}(t)|_{k+1} = \left[g_{(i,j)}^{md}(t) + \delta^{(g)}\left(\mu_i^{md}(t) - \mu_j^{md}(t) - \eta_{(i,j)}^{md}(t) \right)\right]_k^+$$

$$f_{(i,j)}^{m}(t)|_{k+1} = \left[f_{(i,j)}^{m}(t) + \delta^{(f)}\left(\sum_{d\in D} \eta_{(i,j)}^{md}(t) - \beta_{(i,j)}(t) \right)\right]_k^+$$

3) Transmitter Set Scheduling:

$$\lambda^{\alpha}(t)|_{k+1} = \left[\lambda^{\alpha}(t) + \delta^{(\lambda)}\left(\sum_{(i,j)\in E} \beta_{(i,j)}(t) C_{(i,j)}^{\alpha}(t) - \theta(t) \right)\right]_k^+$$

4) Dual Variable Update:

$$\boldsymbol{\vartheta}|_{k+1} = \left[\boldsymbol{\vartheta} - \delta^{(\vartheta)} \frac{\partial L(\mathbf{R}, \mathbf{g}, \mathbf{f}, \boldsymbol{\lambda}, \boldsymbol{\vartheta})}{\partial \boldsymbol{\vartheta}} \right]_k^+$$

Note that $[\cdot]^+$ is not applied to the update iteration of μ.

IV. Experimental Results

In this section, performance of the proposed dynamic cross-layer algorithm (PDCA) is compared to two baseline schemes: 1) LATR, layered multicast algorithm [3] based on traditional routing and link conflict graph in [11]; and 2) JAOR, joint source and flow rate optimization algorithm [4] based on OR in [7]. It should be noted that OR is not considered in the original formulation of [4]. Here we integrate OR into JAOR to achieve better performance than that proposed in [4]. Alternatively, the key difference among these three schemes is that JAOR/LATR are based on static networks with/without OR, respectively, while PDCA considers the practical dynamic networks with OR. The wireless network topology is shown in Fig. 1(b), with a source node, three relay nodes and three destination nodes. The transmission rate for each transmitter node is set to 7.5 Mbps, and the packet reception rate of each link is varied over different time slots. At the source node, we use Joint Scalable Video Model 7_10 reference codec of H.264/AVC extension standard, to encode three well-known test-sequences (*Bus*, *Football*, and *Foreman*) at frame rate of 30 frames per second, CIF (352×288) resolution, and a GOP-length of 32 frames. These sequences are encoded with 256 Kbps at base layer, and 384Kbps, 512Kbps and 1024Kbps at three enhancement layers by fine granularity scalable coding.

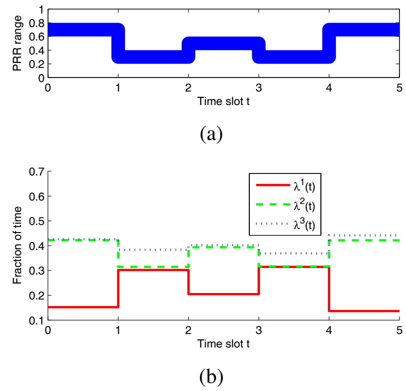
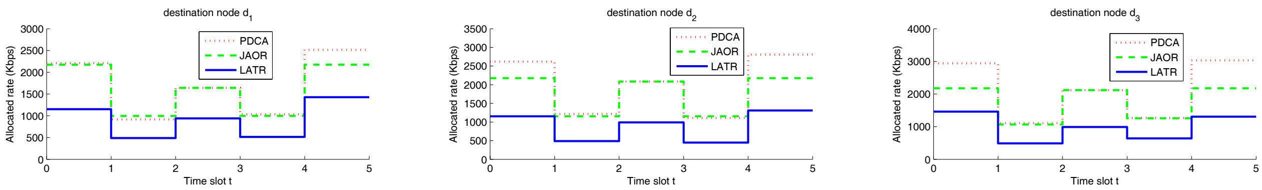


Fig. 2. (a) Dynamic PRR range of wireless links, (b) optimal time fraction of maximum CTSs scheduled by the proposed dynamic cross-layer algorithm.

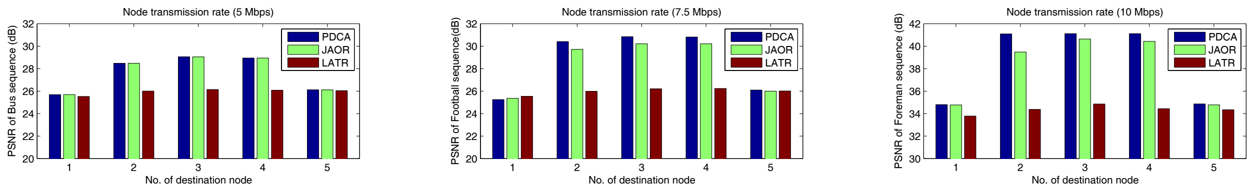
We divide the SVC streaming period into five time slots. Assume that within each time slot, the wireless network can transmit in one of three states (namely, good state, fair state, and poor state, with PRRs of wireless links randomly generated within the range of $0.6 \sim 0.8$, $0.4 \sim 0.6$, and $0.2 \sim 0.4$, respectively). Fig. 2(a) indicates the simulated network condition with PRR range at each time slot. The optimal time fraction of three maximum CTSs scheduled by the proposed algorithm is shown in Fig. 2(b), where $\Gamma^1(t) = \{n_1, n_3\}$, $\Gamma^2(t) = \{n_2\}$, and $\Gamma^3(t) = \{s\}$. It can be seen that, when the network condition is good with higher PRRs (e.g., at $t = 1$ and $t = 5$), the proposed algorithm would schedule more transmission time for senders with more next-hop nodes (e.g., node n_2). In contrast, when the network condition is not good, wireless links are unreliable with lower PRRs. At this time, the proposed algorithm could increase the utilization of other senders (e.g., nodes n_1 and n_3) to combine multiple weak links into one strong link.

Fig. 3 shows the reception rates allocated by different algorithms. By PDCA and JAOR, more video reception rate is allocated for each destination node at each time slot than LATR. Such network multicast throughput gain is achieved due to the key difference between OR and traditional routing. That is, with OR the wireless shared medium time utility is enhanced by allowing multiple neighbor nodes to forward a packet opportunistically, which in turn makes throughout take place concurrently at multiple outgoing links from the same transmitter. With traditional routing, in contrast, since one transmitter can not simultaneously send a packet to multiple relay nodes due to wireless link interference, the node transmission



(a) (b) (c)

Fig. 3. Comparison of allocated rate for destination (a) d_1 (b) d_2 and (c) d_3.



(a) (b) (c)

Fig. 4. Comparison of received PSNR of (a) *Bus* sequence at 5 Mbps, (b) *Football* sequence at 7.5 Mbps, and (c) *Foreman* sequence at 10 Mbps.

capacity is constrained by one of its outgoing links with the highest transmission rate. Compared to JAOR, the network multicast throughput (i.e., total video reception rate allocated for all destinations) is further improved by PDCA. This is because PDCA considers the network dynamics and optimizes the total network utility in the form of video reception qualities by balancing and adapting network flow over all time slots within the SVC steaming period, while JAOR only individually optimizes within each time slot. When network condition is not good, both algorithms assign the same amount of reception rate for destinations. Within time slot with higher PRRs (e.g., at $t = 1$ and $t = 5$), however, PDCA allocates more data rate than needed for that time slot and reserve such extra rate for time slots with bad conditions to increase the overall utility, while JAOR fails to do so because all four video layers are already fully received at $t = 1, t = 5$ and no more rate will be allocated.

For evaluation within a more general network, we further generate a wireless network with 15 nodes randomly distributed in a $100m \times 100m$ square region and different node transmission rates. We fix the node nearest to the lower left corner as the source node, and select five nodes as destination nodes. The effective transmission range D_t is assumed to be 50 m. In Fig. 4, we investigate the video reception qualities at different node transmission rates, while the dynamic PRR range of links within each time slot is the same as in Fig. 2(a). Similarly, it can be observed that PDCA outperforms the other two algorithms with higher overall video reception quality in peak signal-to-noise ratio (PSNR) for all destinations. However, we can see from Fig. 4(a) that when the node transmission capacity is relatively low (e.g., 5 Mbps), due to the rate bound constrained by each source-destination pair's end-to-end throughput, there is no extra rate region for PDCA to balance reception rate over different time slots even at time slots with good network condition. At this time, both PDCA and JAOR achieve the same performance.

V. Conclusion

For dynamic wireless networks, we proposed a joint optimization scheme for SVC multi-rate multicast based on OR and network coding, to maximize the overall video reception quality among all destinations over the multicast periods. The decision of optimal routes for SVC layered streaming has been integrated into the joint optimization formulation with OR. With the dynamic wireless link states either known or predicted, the proposed scheme jointly optimized the reception rate, routes to each destination, and time fraction of maximum CTSs. We developed a distributed dynamic cross-layer algorithm by using dual decomposition and primal-dual update approach. Simulation results have demonstrated network multicast throughput improvement and adaptation to dynamic network changes.

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