ABSTRACT

In this paper, we formulate the cross-layer optimization for delay-sensitive media transmission over time-varying wireless channels as a finite-horizon Markov decision process (MDP) by explicitly considering the users’ heterogeneous multimedia traffic characteristics (e.g., delay deadlines, distortion impacts and dependencies etc.) and time-varying network conditions. Based on the heterogeneous characteristics of the media packets, we are able to express the transmission priorities between packets as a new type of directed acyclic graph (DAG). This DAG provides the necessary structure for determining the optimal cross-layer actions in each time slot. The simulation results demonstrate that the proposed solution significantly outperforms existing state-of-the-art cross-layer solutions.

Index Terms-- Multimedia Streaming, Optimal Stopping, Directed Acyclic Graph.

I. INTRODUCTION

One of the key challenges associated with the robust and efficient multimedia transmission over wireless networks is the dynamic characteristics of both the wireless networks and multimedia sources experienced by the wireless user [1].

To take into consideration the heterogeneous characteristics of the multimedia data, one solution is to employ Unequal-Error-Protection (UEP) techniques [4] using Forward Error Control (FEC) to differentially protect the video packets based on their distortion impacts, delay deadlines and packets’ dependencies. In [3], the complicated dependencies between the multimedia packets are expressed as a DAG and the packet scheduling is optimized under a rate-distortion framework (named RaDiO), which takes into consideration the heterogeneous characteristics of multimedia data. However, these solutions assume only simplistic underlying network (channel) models (e.g. constant transmission rate and packet loss rate) and they do not consider the time varying channel conditions and the adaptation of transmission parameters at the other layers of the network stack, besides the application (APP) layer. In [10], the authors proposed channel, distortion and delay deadline aware scheduling. However, we note that this approach made simple assumptions (e.g. one video frame at each queue and static channel model).

In this paper we develop a cross-layer optimization framework for single-user multimedia transmission over single-hop wireless networks by explicitly considering the heterogeneous characteristics of multimedia data, time-varying network conditions and adaptation capability of the user at the various layers of the protocol stack. Specifically, we first consider the cross-layer optimization for a single-packet transmission and formulate it as a finite-horizon optimal stopping problem in which the threshold-based cross-layer transmission policy is determined.

We then extend the cross-layer optimization for the single packet to multiple packets, each having different attributes (e.g. arrival times, delay deadlines, distortion impact and dependencies). Accordingly, the multi-packet cross-layer optimization is formulated as multiple dependent optimal stopping problems. In addition to exploiting future potential transmission opportunities as in single-packet transmission for each packet, we also have to consider the mutual impact among multiple packets (i.e. determining which packets should be transmitted first) due to their dependencies and their sharing of the same transmission resource (e.g. transmission power etc.). To do this, we define the transmission priorities between the packets based on their attributes, and express the transmission priorities as a DAG, which can be viewed as an augmented DAG expression of the packet dependencies proposed in [3]. The proposed DAG expression of the packets’ priorities provides the necessary structure for determining the optimal cross-layer actions at each time slot. Specifically, we will always select the root packet in the DAG to transmit since it has the highest marginal utility.

The paper is organized as follows. Section II characterizes the attributes of the multimedia traffic. Section III formulates the single-packet cross-layer optimization as an optimal stopping problem and proposes a novel threshold-based scheduling policy. Section IV formulates the transmission of multiple packets as an MDP and presents structural properties of the corresponding solutions. Section V presents the simulation results, which is followed by the conclusions in Section VI.

II. A BRIEF OVERVIEW OF MULTIMEDIA TRAFFIC CHARACTERISTICS

In this section, we discuss how the heterogeneous attributes of multimedia traffic can be modelled. As in [6][7], the multimedia data are often encoded interdependently, using sophisticated prediction-based coding solutions, in order to remove the temporal correlation existing among the data. This introduces sophisticated dependencies between the encoded data across time. In [3], multimedia traffic is modelled using a DAG, which takes into account the distortion impact and delay deadline of each packet, as well as the inter-dependencies among packets, thereby accurately capturing the time-varying traffic characteristics. In this paper, we also use a DAG to characterize the traffic. The encoded data is packetized into multiple data units (DUs). For example, for video applications, the DUs are video packets, video frames etc. The DU’s attributes are listed below:

- **Size**: The size of DU $\mathcal{J} \in \mathbb{N}$ is denoted as $l_{\mathcal{J}}$ (measured in bits).
- **Distortion impact**: Each DU $\mathcal{J}$ has a distortion impact $d_{\mathcal{J}}$, which is the amount by which the video distortion will be reduced if the DU is decoded at the destination.
- **Arrival time**: The arrival time is the time at which the DU is ready for transmission and denoted by $t_{\mathcal{J}}$ for DU $\mathcal{J}$.
- **Delay deadline**: The delay deadline is the time by which the data unit must be decoded and displayed. If the DU is not received at the destination by the delay deadline, it will be discarded and it will be considered useless. The delay deadline

$^{1}$ In real multimedia applications, the discard data can be concealed using previous received data. The error concealment algorithm can be easily

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is denoted by \( d_j \) and \( t_j < d_j \), since the DU needs to be transmitted before its expiration.

- **Dependency**: The dependencies among the DUs are expressed as a DAG as in [3]. In this paper, we assume that, if DU \( j \) depends on DU \( j' \) (i.e. there exists a path directed from DU \( j' \) to DU \( j \) and denoted by \( j \leadsto j' \)), then \( t_j \leq t_{j'} \) and \( d_j \leq d_{j'} \). In other words, DU \( j \) should be encoded and decoded prior to DU \( j' \). If DU \( j \) is not successfully transmitted prior to the delay deadline, then all the DUs depending on DU \( j \) will be considered useless.

During the transmission, each DU is packetized into one (or multiple) packet(s). Our cross-layer optimization is performed at the packet level. With abuse of notation, we consider that each packet \( j \) (instead of DU \( j \) ) has size \( l \), distortion impact \( q_j \), arrival time \( t_j \), delay deadline \( d_j \) and its dependencies to other packets are expressed by a DAG\(^2\).

### III. SINGLE PACKET TRANSMISSION

Without loss of generality, let us consider a packet \( j \) with \( t_j = 0 \). The packet can be scheduled for transmission at time slots \( 0, 1, \ldots, d_j \). We define a scheduling policy \( \pi_j = (\pi_j^1, \pi_j^2, \ldots, \pi_j^{d_j}) \in \{0, 1\}^{d_j+1} \), whose components \( \pi_j^i \) represent the scheduling action taken in time slot \( i \) : \( \pi_j^i = 1 \) if the packet is transmitted, and \( \pi_j^i = 0 \), otherwise. The packet scheduling policy is performed at the APP layer. In each time slot \( t \), the user experiences a channel condition \( h_i \in \mathcal{H} \), where \( \mathcal{H} \) is the set of finite possible network conditions (or channel conditions). In this paper, we assume that the channel condition \( h_i \) can be modelled as finite state Markov chain (FSMC) [8] with transition probability \( p_{hh'}(h_i \mid h) \in \{0, 1\} \). At time slot \( t \), if the packet is scheduled to be transmitted (i.e. \( \pi_j^i = 1 \)), the wireless user deploys the transmission strategy \( a_i \in \mathcal{A} \), where \( \mathcal{A} \) is the set of possible transmission strategies available for the user. The transmission strategies can include the modulation and channel coding selection or power allocation at the physical layer, or retransmission at the MAC layer. The incurred transmission cost (e.g. the amount of transmission time or the amount of power allocated) is denoted by \( \rho_j(h, a_i) \).

The objective of the cross-layer optimization for the single packet transmission is to maximize the discounted net utility, i.e.

\[
\max_{\pi_j \in \{0, 1\}^{d_j+1}} \sum_{t=0}^{d_j} \alpha^t (q_j - \rho_j(h_i, a_i)) \pi_j^t, \quad \text{s.t.} \quad \sum_{t=0}^{d_j} \pi_j^t \leq 1, \quad r(h_i, a_i) = \pi_j^t, \tag{1}
\]

where \( r(h_i, a_i) \) is the average amount (in bits) of successfully transmitted data at time slot \( t \). \( \alpha \in [0, 1] \) is the discount factor. The first constraint in Eq. (1) means that the packet is scheduled for transmission within one time slot. This is because we assume that the packet scheduling is performed at the APP layer and we do not need to consider APP layer retransmissions, which can be instead implemented more efficiently at the MAC layer in this one-hop wireless network. The second constraint means that, once the packet is scheduled for transmission at time slot \( t \), i.e. \( \pi_j^t = 1 \), the transmission strategy \( a_i \) is selected such that the total number of successfully transmitted bits equals the length of the packet. Note that the packet scheduling \( \pi_j^t \) and transmission strategy \( a_i \) need to be jointly optimized in order to maximize the net utility.

It is clear that the cross-layer optimization in Eq. (1) can be formulated as a finite horizon optimal stopping problem [5], which is a special MDP. Specifically, we define the traffic state of the packet at time slot \( t \) as \( b_j^t \in \{0, 1\} \), where \( b_j^t = 0 \) if the packet is successfully received by the destination, and otherwise \( b_j^t = 1 \). \( b_j^{t-1} = 0 \) is the stopping state in which no future transmission is required for this packet. We define the state of packet as \( s_j^t = (b_j^t, h_i^t) \), which include the traffic state \( b_j^t \) and channel state \( h_i^t \). Since both \( b_j^t \) and \( h_i^t \) are Markovian, the transition of the state \( s_j^t \) is also Markovian and the state transition probability is given by \( p(s_j^{t+1} \mid s_j^t, \pi_j^t) = p(b_j^{t+1} \mid b_j^t, \pi_j^t) p(h_i^{t+1} \mid h_i^t) \). The action at each state is \( \pi_j^t \).

For the cross-layer optimization for the single-packet transmission, the optimal solutions have the following properties stated in Theorem 1.

**Theorem 1** (i) The optimal packet scheduling policy is a threshold-based policy, i.e.

\[
\pi_j^t^\star((h_i^t)) = \begin{cases} 1 & \text{if } q_j - \lambda \rho_j(h_i^t, a_i^t) > \pi_j^t(h_i^t) \\ 0 & \text{otherwise} \end{cases}
\]

where \( \pi_j^t(h_i^t) = \alpha \sum_{h_i^{t+1}} p(h_i^{t+1} \mid h_i^t) U_j^t((1, h_i^{t+1})) \), \( U_j^t((1, h_i^t)) \), \( \pi_j^t(h_i^t) \), and \( U_j^s((1, h_i^t)) = 0 \).

Proof: The details of the proof can be found in [9].

From Property (i) in Theorem 1, we note that the optimal packet scheduling policy is determined by comparing the immediate net reward \( q_j - \lambda \rho_j(h_i^t, a_i^t) \) to the average future net reward \( \pi_j^t(h_i^t) \). The immediate net reward is obtained if the packet is scheduled for transmission at the current time slot, while the average future net reward is the discounted average net reward that the wireless user can obtain if the packet is delayed for future transmission. When \( q_j - \lambda \rho_j(h_i^t, a_i^t) > \pi_j^t(h_i^t) \), the wireless user will receive a higher reward if the packet is scheduled for transmission in the current time slot instead of delaying it for future transmission. On the other hand, when \( q_j - \lambda \rho_j(h_i^t, a_i^t) \leq \pi_j^t(h_i^t) \), the wireless user prefers to delay the transmission since, on average, a later transmission will lead to a higher reward.

From (ii), we notice that the average future net reward (i.e. the threshold) is decreased as the delay deadline is approached. This is because, when the delay deadline is far away from the current time, the packet has a higher chance to be transmitted using better channel conditions in the future, and this will result in a lower transmission cost. Hence, the wireless user prefers delaying the transmission by setting a higher threshold for time slots that are further from the deadline.

### IV. MULTI-PACKET TRANSMISSION

In this section, we consider the cross-layer optimization for a group of packets. We consider that there are \( N \) packets for transmission. Each packet \( j \in \{1, \ldots, N\} \) is available for transmission from the time slot \( t_j \) to \( d_j \). Let \( d_{\max} = \max_{1 \leq j \leq N} \{d_j\} \). We define the traffic state as \( B^j = \{b_j^t\}_{1 \leq t \leq \min(d_j, d_{\max})} \), where \( b_j^t \) is defined as in Section III. The traffic state \( B^j \) includes the traffic states of all packets that are available for transmission (i.e. \( t_j \leq t \leq d_j \)) at the current time slot \( t \). Note that the dependencies between packets are automatically embedded in the traffic state. Accordingly, the state of the wireless user is defined as \( s^i = (B^i, h_i^t) \) to include the traffic state and channel state.

\[^3\text{We assume that the channel state transition is independent of the traffic state transition.}\]
scheduling policy at time slot \( t \) is given by \( \pi' = \{ \pi'_j \}_{j \in \mathcal{S}_t} \). Note that within one time slot, there may be multiple packets to be transmitted based on the current traffic state as well as the channel state. The transmission strategy at time slot \( t \) is given by \( \alpha' \). The cross-layer action is denoted by \( \sigma' = \{ \sigma'_j \}_{j \in \mathcal{S}_t} \). The transmission cost is given by \( \rho' \left( \sum_{j \in \mathcal{S}_t} \pi'_j h'_j, a'_j \right) \), where \( \rho' \) depends on the bitstream length of the transmitted packets, the current channel condition and the current transmission strategy. Then, the immediate net reward at each time slot is given by

\[
u'(B', \sigma') = \sum_{j \in \mathcal{S}_t} \mathbb{E}[\alpha' | j] \mathcal{Q} \left( \sum_{j \in \mathcal{S}_t} \pi'_j h'_j, a'_j \right).
\]

The difference between the immediate net reward above and the one for the single packet is that the transmission cost \( \rho' \) is a function of the entire bitstream length of all packets to be transmitted at the current time. Note that the packets can only be transmitted once their parents in the DAG have been transmitted. The cross-layer action is \((\alpha', \sigma')\). The state transition probability is given by

\[
p(s^{t+1} | s^t, \pi') = \prod_{j \in \mathcal{S}_t} p(j'_t | b'_j, \pi'_j) p(h'_t | k).
\]

Note that the packet with \( t_j = t+1 \) will be considered in the next time slot with probability 1 and the packets with \( d_j = t \) will be discarded in the next time slot with probability 1. The objective in this cross-layer optimization is to maximize the accumulated discounted net utility for all the packets, which is presented as follows:

\[
\max_{\sigma' \in \{0,1\}, \alpha' \in \mathcal{A}, \delta \in \mathcal{D}} \sum_{t=0}^{\infty} \alpha t u'(B', \sigma')
\]

s.t. \( \sum_{j \in \mathcal{S}_t} \pi'_j \leq 1, \forall j, r(h'_j, a'_j) = \left( \sum_{j \in \mathcal{S}_t} \pi'_j, \right) (2) \)

\[
b'_j \leq b'_j, \text{if } j \neq j', \forall j.
\]

As before, the first constraint in Eq. (2) means that each packet is scheduled for transmission within one time slot. The second constraint means that, for those packet scheduled for transmission at time slot \( t \), i.e. \( \pi'_j = 1 \), the transmission strategy \( \alpha'_j \) is selected such that the total number of successfully transmission bits equals the bitstream length of the transmitted packets. The third constraint means that the parent packets should be transmitted earlier. Note that the packet scheduling \( \pi' \) and transmission strategy \( \alpha' \) should be jointly optimized in order to maximize the net utility.

In Section III, we have already answered the question: at what time should a packet be transmitted when performing single-packet cross-layer optimization? In the multi-packet cross-layer optimization, we are interested in the question: which packet should be transmitted first? In order to determine the transmission orders for the packets, we first define the marginal utility for packet \( j \) at time slot \( t \), if it is transmitted, as follows:

\[
\Delta u'_j(s^t, \sigma'_j) = q_j - \lambda p'(s^t, \sigma'_j) - \overline{\mathcal{Q}}(s^t, \sigma'_j)
\]

where \( \sigma'_j \) is the cross-layer action for the packets except packet \( j \), \( \overline{\mathcal{Q}}(s^t, \sigma'_j) \) is the net utility the wireless user can obtain if it delays the packet transmission, serving as a threshold used to determine whether packet \( j \) is scheduled for transmission or not, which is similar to the threshold for single-packet transmission. \( q_j - \lambda p'(s^t, \sigma'_j) \) is the net utility if packet \( j \) is scheduled at time slot \( t \). Note that \( \overline{\mathcal{Q}}(s^t, \sigma'_j) \) and the transmission cost \( \rho'(s^t, \sigma'_j) \) may depend on the cross-layer actions of other packets that can be transmitted at the current time slot. Then, the marginal utility \( \Delta u'_j(s^t, \sigma'_j) \) is the amount by which the utility can be increased if the packet is transmitted at the current time slot \( t \) rather than delaying it for future transmission. From Section III, we know that, for the single-packet transmission, if \( \Delta u'_j(s^t, \sigma'_j) = \Delta u'_j(1, h'_j) > 0 \), then the packet is scheduled for transmission. Using the marginal utility, we are able to formally define the transmission priorities between packets as follows.

**Definition (Transmission Priority):** Packet \( j \) has a higher transmission priority than packet \( k \) (denoted by \( j < k \)) at time slot \( t \) if \( \Delta u'_j(s^t, \sigma'_j, \sigma'_j, j, k) \geq \Delta u'_k(s^t, \sigma'_j, \sigma'_j, j, k) \) for \( \forall s^t \) and \( \sigma'_j, j, k \) and where \( \sigma'_j \) means that packet \( k \) is not transmitted and \( \sigma'_j, j, k \) is the cross-layer action of other packets, except packets \( j \) and \( k \).

The transmission priority defined above indicates that, if both packets \( j \) and \( k \) are available for transmission and \( b'_j = b'_k = 1 \) at time slot \( t \), then packet \( j \) will be transmitted before packet \( k \) under any channel conditions. Note that it is possible that both packets can be transmitted at time slot \( t \). Based on the transmission priority definition, we have the following lemmas:

**Lemma 1:** If \( j < k \), then \( j < k \).

Proof: see [9].

From Lemma 1, we note that, if packet \( j \) depends on packet \( j \), then packet \( j \) will be transmitted earlier than packet \( k \). It is obvious since, in order to decode packet \( k \), packet \( j \) must be available at the destination. We further note that, after introducing the interdependency, the packets \( j \) and \( k \) satisfy \( q_j \geq q_k \) and \( d_j \leq d_k \). packet \( j \) may not have a higher priority than packet \( k \).

However, we have the following lemma that enables us to compare the priorities of different packets.

**Theorem 2**: The optimal packet scheduling policy in state \( s^t = (B^t, h^t) \) can be computed by repeating the following two phases.

**Phase 1:** Select the packet with the highest marginal utility from the roots of DAG \( \mathcal{P}G^t \) to transmit:

\[
j_k = \arg \max_{j \in \text{root}(\mathcal{P}G^t)} \{ \Delta \overline{\mathcal{P}}(\mathcal{P}G^t, h^t) \}
\]

**Phase 2:** Determine whether the best packet to be transmitted or not:

\[
\pi'_h = \begin{cases} 1 & \text{if } \Delta \overline{\mathcal{P}}(\mathcal{P}G^t, h^t) > 0 \\ 0 & \text{o.w.} \end{cases}
\]

where the marginal utility is given by

\[
\Delta \overline{\mathcal{P}}(\mathcal{P}G^t, h^t) = q_k - \lambda \rho(\mathcal{P}G^t) h^t - \rho((k-1) l, h^t) + \pi'(\mathcal{P}G^t) - \pi''(\mathcal{P}G^t, h^t)
\]

and \( \pi''(\mathcal{P}G, h) \) is the post-state value function for the state corresponding to the DAG \( \mathcal{P}G \) and current channel state \( h \), which is similarly defined as in Theorem 1. \( \mathcal{P}G^t \) is computed by \( \mathcal{P}G^t = \mathcal{P}G^{t-1} (j_k) \) and \( \mathcal{P}G^0 = \mathcal{P}G \). 

Proof: The proof can be found in [9].

Theorem 2 indicates that the packet which is available for transmission and has higher transmission priority is always transmitted earlier, no matter what channel state it experiences. This transmission priority significantly simplifies the way to solve...
the cross-layer optimization in terms of both the computation complexity and storage overhead (see the details in [9]).

V. SIMULATION RESULTS

In this section, we perform a numerical experiment to compare the performance of various state-of-art solutions for multimedia communications with the proposed framework.

We compare our proposed cross-layer solution with several start-of-art solutions which only consider either the media characteristics or the time-varying channel conditions. In the experiment, to compress the video data, we used a scalable video coding scheme [7], which is attractive for wireless streaming applications because it provides on-the-fly application adaptation to channel conditions, support for a variety of wireless receivers with different resource capabilities and power constraints, and easy prioritization of various coding layers and video packets. We choose for this experiment two video sequences (Foreman, Mobile at CIF resolutions, 30 frames/second), exhibiting different motion activities. The video sequences “Foreman” is encoded at the bit rate of 512 kbps and “Mobile” is encoded at 1024 kbps. Each Group of Picture (GOP) contains 8 frames and each encoded video frame can tolerate a delay of 266ms corresponding to the duration of GOP. The transmission cost is the amount of power consumed during the packet transmission. The normalized channel gain varies from 0 to 1 and is modelled as in [8] as a FSMC with 5 states. The cross-layer action includes the packet scheduling at the APP layer and power allocation at the PHY layer. The transmission strategies at the MAC are not considered here. We consider three comparable solutions: (i) our proposed cross-layer solution which takes into account both the heterogeneous multimedia traffic characteristics (e.g. delay deadlines, distortion impacts and dependencies etc.) and time-varying network conditions; (ii) the cross-layer solution [2] which only considers the distortion impact of each media packet and adapts the transmission strategies based on the observed channel conditions; (iii) the solution performing the rate-distortion optimization assuming the constant channel conditions (i.e. using average channel conditions) as in RaDiO [3].

In Figure 1 (a)-(b), we show the Peak-Signal-to-Noise Ratio (PSNR)-energy curves under different transmission solutions for the two video sequences. From these figures, we note that our proposed cross-layer optimization solution outperforms both the conventional “distortion-impact”-based solution and rate-distortion optimization assuming constant channel conditions by, on average, around 4dB and 2.5dB in “Foreman”, and 3.5dB and 1.5dB in “Mobile” in terms of PSNR. The improvement comes from the fact that our proposed solution schedules the packets and adapts the transmission strategies (i.e. adapting the power allocation) based on the heterogeneous characteristics of the multimedia packets as well as the time-varying channel conditions. We also notice that the rate-distortion optimization with constant channel conditions obtains higher received video quality than the “distortion-impact”-based solution. It shows that the characteristics (dependencies, distortion impacts and delay constants) of media packets play a very important role in improving the media quality.

VI. CONCLUSIONS

In this paper, we formulate the problem of cross-layer optimization for delay-sensitive packetized media applications as a finite-horizon Markov decision process. Based on the heterogeneous characteristics of the media packets, we express the transmission priorities between packets as a DAG. Using the DAG expression, we are able to derive an optimal cross-layer solution by simply and recursively selecting the packet from the root of the priority graph having the highest marginal utility. The simulation results show that the proposed cross-layer optimization solution significantly outperforms the start-of-art solutions which (partially) ignore the media characteristics and time-varying network conditions.

REFERENCES


