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SPECIAL ISSUE PAPER

Stochastic stable buffer control for quality-adaptive HEVC video transmission in enterprise WLAN architectures

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Abstract Transmission of high efficiency video coding (HEVC) video streams over error-prone enterprise wireless local area networks (WLAN) architectures is challenging because of the difficulties in buffer overflow management in the switches within enterprise WLAN architectures. Thus, this paper proposes a new quality-aware video transmission method for company-wide enterprise WLAN architectures by combining video transmission technologies with a distributed stochastic buffering model that jointly controls power consumption and queue stabilization. After conducting extensive simulations with HEVC test sequences, significant video quality improvements are observed with the average Y-PSNR gain of 3.33 dB.

Keywords High efficiency video coding (HEVC) · Stochastic control · Power-awareness · Enterprise WLAN

1 Introduction

Cisco visual networking index (VNI) anticipated that the summation of all various forms of video contents will be in the range of 80–90 % of global consumer traffic by 2017, and the traffic from wireless and mobile devices will exceed the traffic from wired devices by 2016 as explained in [1]. Among various forms of video contents, high efficiency video coding (HEVC) becomes one of the major sources in mobile and consumer electronics applications [2]. After successfully standardizing H.264/AVC [3], ISO/IEC MPEG and ITU-T VCEG have been jointly developing next-generation video coding standard called HEVC [4]. This new standard targets next-generation HDTV displays and IPTV services, addressing the concern of error resilient streaming in HEVC-based IPTV [5–7]. Compared to H.264/AVC, the HEVC standard includes new features such as extended prediction block sizes (up to 64 × 64), large transform block sizes (up to 32 × 32), tile and slice picture segmentations for loss resilience and parallelism, sample adaptive offset (SAO), and so on as presented by [2, 8]. With those new features, this paper evaluates the performance gain of the proposed HEVC video transmission method.

One example of the wireless networking environment is the enterprise wireless local area networks (WLANs) that enable wireless access in company-wide networks equipped with access points (APs), switches, and core-backbone computers as proposed by [9–13]. The enterprise WLAN market is rapidly evolving and discovering potential possibilities including mobile and wireless HEVC video transmission applications and services. In addition, video transmission over wireless networks is one of the promising topics in HEVC research societies [14–16]. However, the HEVC video transmission over the error-prone enterprise WLAN is quite challenging because of the difficulties of buffer overflow control in a switch which is one of the main components within enterprise WLAN architectures. Hence, the joint optimization for both video sources (servers) and switches is essential as discussed by [17–20]. For example, the switches in enterprise WLAN manage their internal buffer occupancies by deciding data transmission power to next hop switch, and the buffer management

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reduces the ratio of packet drops that influences the quality of service (QoS) for video transmission, significantly.

For the joint optimization, this paper (i) utilizes a distributed stochastic buffer model (DSBM) which is initially introduced by [21] which controls the buffers of switches optimally by reducing buffer overflows that degrade HEVC video quality significantly, and (ii) extends the functionality of the DSBM to support not only switches but also HEVC video source(s) in enterprise WLAN architectures.

The rest of this paper is organized as follows: Sect. 2 briefly introduces preliminary information in terms of previous work for stochastic buffer management in distributed networks. Section 3 presents our proposed distributed stochastic buffer control algorithm for quality-aware HEVC video transmission over enterprise WLAN architectures. Section 4 evaluates the performance of the proposed distributed stochastic buffer control algorithm with HEVC test sequences. Section 5 concludes this paper.

2 Previous work

Various stochastic buffering algorithms have been investigated for utility–delay tradeoffs as proposed by [21–23].

The proposed distributed stochastic buffering algorithm proposed by [21] also controls buffers in terms of power–delay tradeoffs in enterprise WLAN architectures. However, the proposed algorithm by [21] is different from the proposed algorithm in this paper as follows: (i) considered Shannon's in [21] is formulated with natural logarithm whereas the correct form is using logarithm with the base of 2 (see (3) in Sect. 3); (ii) the background noise is not statistically considered in [21]; (iii) the equation (11) in [21] is not correct and the correct form is as follows;

$$\min : \sum_{i=1}^{\mathcal{N}} \left(\alpha \overline{P}_i + \sum_{j \in \mathcal{S}_i^{next}} \mu_{i \rightarrow j}(t) \big(B_j(t) - B_i(t) \big) \right) \tag{1}$$

and (iv) the proposed algorithm in [21] is not for video streaming. Therefore, the performance evaluation in [21] is not for video streaming as well. However, the proposed algorithm in this paper is for HEVC video transmission. Thus, the evaluation of the proposed algorithm in this paper is performed based on real HEVC test sequences.

The stochastic buffering algorithm in [22] is for robust and autonomous multi-hop routing in mobile robotics platforms. In the considering system in [22], the buffers are connected via 60 GHz wireless links (not wires). Thus, the considering environments are totally different from each other. Since the stochastic buffering algorithm proposed by [22] considers 60 GHz specific characteristics (including path-loss, propagation attenuation by oxygen, etc.), the corresponding numerical formulations are totally different from each other, too. Moreover, the performance evaluation in [22] is not considering video streaming as well.

The stochastic buffering algorithm in [23] is for joint source coding and uplink data transmission in cloud radio access networks. In considering system in [23], the buffers are connected via wireless interference links (not wires). Thus, the considering environments are totally different from each other. In addition, the performance evaluation in [23] does not consider video streaming features as well. Moreover, the considering cloud radio access network architecture in [23] is for one-hop data transmission (from multiple radio units to one cloud unit) whereas this paper considers multi-hop routing mechanisms.

3 Proposed method

In the general architecture of video transmission system platforms, video sources are located in the highest level of the hierarchical switching structure within enterprise WLAN architectures as illustrated in Fig. 1. The video source will be delivered to a sending buffer within the switches in enterprise WLAN architectures as presented in Fig. 2, and the video source will be eventually delivered to end users as shown in Fig. 3. In this proposed architecture, each switch observes the buffer occupancy of itself and next-hop switches. In this case, the video source transmits video packets to the next hop switches that have finite-sized internal buffers (first-in-first-out (FIFO) queues) and could have some error-resilient video transmission methods

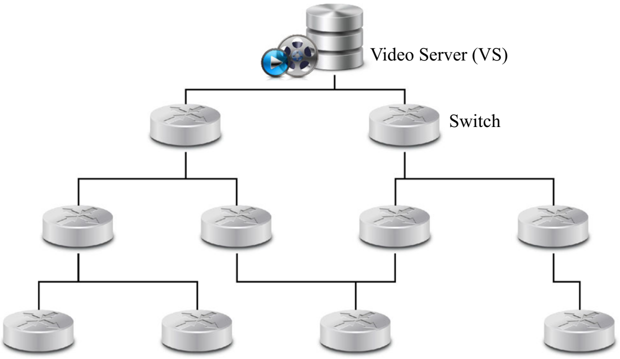

Fig. 1 An example of video server and switches in enterprise WLAN architectures

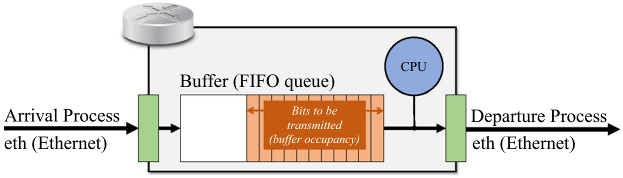

Fig. 2 A reference switch architecture

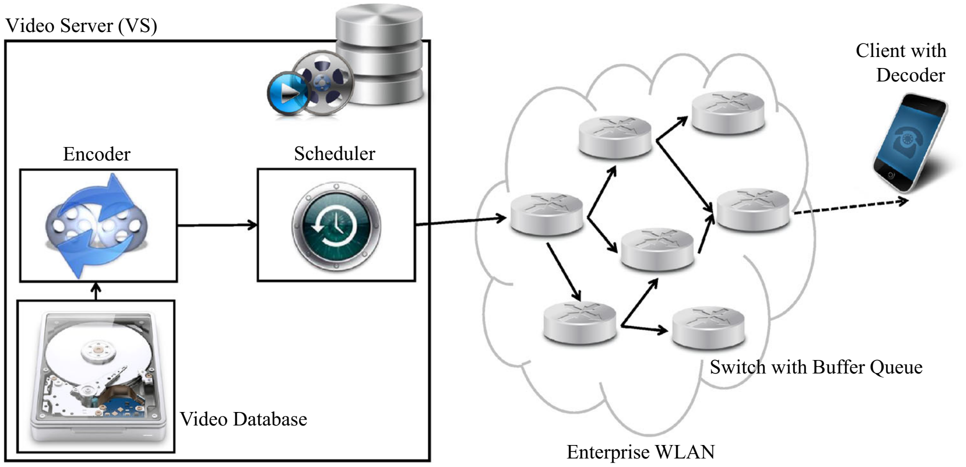

Fig. 3 A proposed system of a video server and enterprise WLAN architectures

such as an unequal error protection (UEP) with forward error correction (FEC) codes and selective channel allocation as discussed by [24].

To make internal buffers (i.e., FIFO queues) be stable and energy efficient, the proposed DSBM stochastic algorithm provides joint stochastic optimization of (i) the minimization of the summation of time average energy consumption and (ii) the buffer (FIFO queue) stability within switches in reference enterprise WLAN architectures. For given switches $s_i, \forall i \in \{1, \ldots, N\}$ where N stands for the number of switches in reference enterprise WLAN architectures, discrete-time buffer dynamics can be represented as follows:

$$Q_i(t+1) = \max[Q_i(t) - b_i(t), 0] + a_i(t) \quad (2)$$

where $Q_i(t)$, $a_i(t)$, and $b_i(t)$ denote the queue occupancy (i.e., queue backlog size) at unit time t, the summation of all arrival processes at switch i from previous-hop switches (i.e., $\sum_{k\in \mathsf{P}(i)} \gamma_{k\to i}(t)$ where $\mathsf{P}(i)$ stands for the set of previous-hop switches of switch i and $\gamma_{k\to i}(t)$ stands for the amount of data transmission from switch k to switch i at time t), and the summation of all departure processes from switch i to next-hop switches (i.e., $\sum_{j\in \mathsf{N}(i)} \gamma_{i\to j}(t)$ where $\mathsf{N}(i)$ stands for the set of next-hop switches of switch i). Here, $\gamma_{i\to j}(t)$ depends on the amount of power allocation, i.e.,

$$\gamma_{i\to j}(t) = \mathsf{BW} \log_2\left(1 + \frac{P_{i\to j}(t)}{\sigma^2}\right) \quad (3)$$

where BW means the bandwidth of the channel, $P_{i\to j}(t)$ stands for the power allocation for data transmission from sender switch i to destination switch j, and σ^2 stands for the background noise which can be statistically formulated as a normalized Gaussian distribution with 0 mean and 1 standard deviation.

With this buffer model, the mathematical program for desired stochastic algorithm is as follows because our aim is to minimize the summation of time average expected power consumption, i.e.,

$$\min : \sum_{i=1}^{N} \mathbb{E}_t[P_i] \quad (4)$$

subject to (rate stable), i.e.,

$$\lim_{t\to\infty} \frac{Q_i(t)}{t} = 0, i \in \{1, \ldots, N\} \quad (5)$$

where $\mathbb{E}_t[P_i]$ (i.e., time average expected power consumption) can be formulated as:

$$\lim_{t\to\infty} \frac{1}{t} \sum_{\tau=0}^{t-1} P_i(\tau) \quad (6)$$

and this is equivalent to

$$\lim_{t\to\infty} \frac{1}{t} \sum_{\tau=0}^{t-1} \sum_{j\in \mathsf{N}(i)} P_{i\to j}(\tau). \quad (7)$$

According to the theory of stochastic network optimization proposed by [25], our desired algorithm with our considering objective function (4) can be described as follows: Every unit time slot $t \in \{0, 1, \ldots\}$, ith switch where $i \in \{1, \ldots, N\}$ observes the current buffer backlog size $Q_i(t)$ and make a control decision for power allocation from ith switch to its next-hop jth switch $P_{i\to j}(t)$:

$$\min : \phi \sum_{i=1}^{N} \mathbb{E}_t[P_i] + \sum_{i=1}^{N} Q_i(t)[a_i(t) - b_i(t)] \quad (8)$$

where ϕ is a fixed positive constant which can be set by system requirements. If ϕ is relatively high, the proposed stochastic algorithm is more focusing on energy efficiency. Otherwise, the proposed stochastic algorithm is more

Table 1 The characteristics of test sequences defined by JCT-VC

JCT-VC class	Sequence name	Resolution	fps	Test frames	Sample bit depth
Class A	Traffic	2560 × 1600	30	300	8
	PeopleOnStreet	2560 × 1600	30	300	8
Class B	Kimono	1920 × 1080	24	240	8
	ParkScene	1920 × 1080	24	240	8
	Cactus	1920 × 1080	50	500	8
	BasketballDrive	1920 × 1080	50	500	8
	BQTerrace	1920 × 1080	60	600	8

Table 2 Average Y-PSNR gains of the proposed groups

Sequence name	20[a]		40[a]	
	RA[b]	AI[b]	RA[b]	AI[b]
Class A				
Traffic	2.70	6.20	2.27	4.09
PeopleOnStreet	4.54	8.35	4.71	6.46
Class B				
Kimono	0.29	2.51	1.67	1.31
ParkScene	3.06	4.77	2.02	2.75
Cactus	2.03	4.40	1.97	2.48
BasketballDrive	4.18	3.72	0.04	2.26
BQTerrace	2.29	4.92	3.62	3.38

[a] Buffer unit size

[b] Coding structure

focusing on queue rate stability when ϕ is relatively low. In (8), $\sum_{i=1}^{N} Q_i(t)[a_i(t) - b_i(t)]$ is equivalent to:

$$\sum_{i=1}^{N} \sum_{j \in \mathsf{N}(i)} \gamma_{i \to j}(t)\left[Q_j(t) - Q_i(t)\right] \tag{9}$$

and this updates (8) as follows:

$$\sum_{i=1}^{N} \left\{ \phi \mathbb{E}_t[P_i] + \sum_{j \in \mathsf{N}(i)} \gamma_{i \to j}(t)\left[Q_j(t) - Q_i(t)\right] \right\} \tag{10}$$

and this form is separable; therefore, the detailed distributed stochastic operation is as follows: Every unit time slot $t \in \{0, 1, \ldots\}$, each switch (i) observes its own buffer backlog size $Q_i(t)$, (ii) observes the buffer backlog size of next-hop jth switch $Q_j(t), j \in \mathsf{N}(i)$, and (iii) chooses the amount of power allocation from ith switch to its next-hop jth switch $P_{i \to j}(t)$ which minimizes

$$\phi P_{i \to j}(t) + \gamma_{i \to j}(t)\left[Q_j(t) - Q_i(t)\right] \tag{11}$$

which is equal to

$$\phi P_{i \to j}(t) + \mathsf{BW} \log_2\left(1 + \frac{P_{i \to j}(t)}{\sigma^2}\right)\left[Q_j(t) - Q_i(t)\right]. \tag{12}$$

by (3). This (12) is differentiated by $P_{i \to j}(t)$ and set to 0 for finding a desired optimum closed-form solution in each switch:

$$P_{i \to j}(t) = \frac{\mathsf{BW}}{\phi \ln 2}\left[Q_i(t) - Q_j(t)\right] - \sigma^2. \tag{13}$$

```
Given Information;
  – BW: bandwidth
  – $\phi$: control parameter (fixed positive)
Distributed Stochastic Buffering in Each Switch,
$s_i, \forall i \in \{1, \cdots, N\}$;
$t = 0$;
while $t \le T$ do
    // $T$: the number of discrete time iterations;
    Observes the queue size of previous hop switch
    $Q_j(t)$;
    Observes the queue size of current switch $Q_i(t)$;
    Observes the background noise $\sigma^2$;
    Compute $P_{i \to j}(t)$ with (13) ;
    $P_{i \to j}(t) = \frac{\mathsf{BW}}{\phi}\left[Q_i(t) - Q_j(t)\right] - \sigma^2$;
    Transmit bits with computed transmit power:
    $P_{i \to j}(t)$;
end
```

Algorithm 1: Distributed stochastic buffering in each switch

Figure 3 shows the proposed system of a video server and enterprise WLAN architectures. In Fig. 3, a video server is a video source that contains potentially desired video files. When clients (e.g., smartphones or mobile tablets) request specific video files, the contents will be encoded (by an encoder) and they will be scheduled to go through enterprise WLAN architectures. In the enterprise WLAN architectures, multi-hop switches are located and the user client will eventually receive desired video files via the switches. Each switch has its own buffer (i.e., FIFO queue) and the buffer will be controlled by (13) in each unit time.

Fig. 4 Simulation Results: **a** sequence *ParkScene* QP 22 with proposed group, **b** sequence *ParkScene* QP 22 with control group, **c** sequence *ParkScene* QP 27 with proposed group, **d** sequence *ParkScene* QP 27 with control group

Eventually, the proposed algorithm performs as follows when BW and ϕ are given: In each switch device $s_i, \forall i \in \{1, \ldots, N\}$:

- (i) observes the queue size of previous hop switch $Q_j(t)$, the queue size of current switch $Q_i(t)$, and the background noise σ^2;
- (ii) computes $P_{i \to j}(t)$ by (13).

The pseudo-code of this proposed adaptive queue control algorithm is also presented in Algorithm 1.

4 Implementation and experimental results

The proposed adaptive video transmission method based on DSBM guarantees more buffer stability with lesser packet loss rate (PLR). This paper evaluates the performance gain by experimenting two transmission methods;

- (i) proposed group: HEVC transmission with DSBM,
- (ii) control (comparison) group: HEVC transmission without DSBM.

This paper implements picture-level error concealment (EC) method in the reference software of HEVC (HM-11.0), a successor to H.264 advanced video coding (AVC), and the HEVC was standardized as a next-generation video coding technology in April 2013.

This paper also implements the DSBM by extending the study in [21]. The implemented EC method conceals lost pictures caused by buffer overflows in switches with the closest previous picture in the reference picture lists of a decoder. For the simulation-based performance evaluation, (i) three quantization parameter (QP) values (27, 32, and 37), (ii) seven test sequences (Class A and B) as presented by [26] of the common test condition defined by the joint collaborative team on video coding (JCT-VC), and (iii) two coding structures (random access (RA) and all intra (AI)) are used. Table 1 shows the detailed characteristics of test sequences defined by JCT-VC. Note that BW in (13) is set to 2 mega-bits per seconds (Mbps).

Table 2 shows average gain of 3.33 dB in Y-PSNR (dB) for both class A and B sequences and both coding structures RA and AI. In this experimental study, the average video packet size is set to 1400 bytes with the consideration of IP-level fragmentation. The size of buffer unit in switches is calculated by multiplying the packet size to different buffer unit sizes (20 and 40).

Figure 4 illustrates the visual comparison of the test sequence '*ParkScene*'. With given QP values (22 and 27), the proposed group shows noticeable visual differences compared to the control group.

Figure 5 depicts the performance comparison of test sequence '*ParkScene*' between the proposed and control

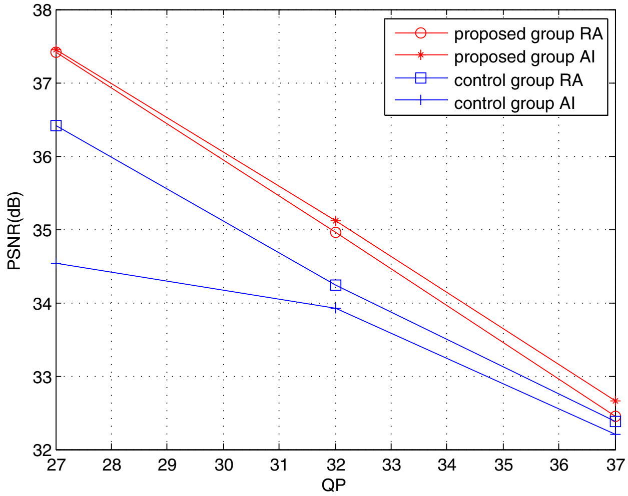

Fig. 5 Performance comparison of the proposed group against the control group with different coding options (*ParkScene*)

(comparison) groups on different coding structures and QP values. Proposed groups always show better video qualities than control (comparison) groups under the condition of all QP values and coding structures (RA and AI). The proposed groups had lesser PLRs (≊0.98 %) compared to the control (comparison) groups (≊3.07 %).

5 Conclusions and future work

This paper (i) utilizes a distributed stochastic buffer model (DSBM) which controls the buffers of switches optimally by minimizing buffer overflows and power consumption and (ii) extends the functionality of the DSBM to support the video source in enterprise WLAN architectures. This paper uses next-generation video coding technology HEVC for experiments, and implements the DSBM, EC module, and packet loss simulators in HEVC reference model software (HM-11.0). The experimental performance evaluation shows that the proposed stochastic buffer management mechanism significantly improves video quality about 3.33 dB in average Y-PSNR. In conclusion, this paper provides a new robust real-time video transmission method over error-prone enterprise WLAN architectures using the DSBM.

As a future research direction, we will verify the proposed stable stochastic buffering with large-scale HEVC test sequences.

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