Traffic scheduling for multimedia transmission over IEEE 802.11e wireless LAN

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Abstract: As the demand for broadband multimedia wireless is increasing, improving the quality of service (QoS) of the widely deployed IEEE 802.11 wireless LAN has become crucial. In order to attain the QoS required by a wide range of applications, the IEEE 802.11 working group has defined a new standard – the IEEE 802.11e. However, very limited work has been performed to address the QoS transmission problem of real-time video over IEEE 802.11e. A novel measurement-based dynamic transmission opportunity (MBDTXOP) scheme is proposed, which adaptively allocates resources to a variable bit rate (VBR) video on the basis of the estimation of future traffic demand to support efficient QoS transmission of VBR video. The novelty of the proposed scheme, when compared with existing methods, lies in estimating the required network resources by exploiting the characteristics of digital video; this capability enables the MBDTXOP scheme to substantially increase network utilisation while preserving the required QoS for the transmission of VBR video. Simulations comparing the proposed scheme with other mechanisms clearly demonstrate the outstanding performance of the former.

1 Introduction

Recently, the widespread use of portable computers, PDAs and handheld devices has led to a rapid growth of Wireless LANs (WLANs). WLANs are now widely used as they provide high mobility, scalability, flexibility and ubiquity. Therefore WLANs are considered as an extension to the existing wired networks and are expected to support the same applications. These applications including voice over internet protocol (VoIP), compressed video and video conferencing, create an imperative demand for service guarantees from WLANs. In particular, moving picture experts group (MPEG) videos – the predominant standard [1] for providing digital video services – have been widely adopted in computer imaging, consumer electronic devices, and broadband video distribution networks. However, owing to the limited capabilities of WLANs and characteristics of MPEG videos such as burstiness and long-range dependence [2], the efficient transmission of MPEG videos and guaranteeing their quality of service (QoS) over WLANs become difficult.

The original IEEE 802.11 WLAN standard [3] is a best-effort network and does not support QoS guarantees for time critical applications [4]. To tackle the QoS issues in the medium access control (MAC) layer, IEEE 802.11 Working Group E has defined a supplement to the 802.11 MAC – the 802.11e [5]. The IEEE 802.11e standard introduces a new hybrid co-ordination function (HCF) that includes two mechanisms: enhanced distributed channel access (EDCA) and HCF-controlled channel access (HCCA). The EDCA is a contention-based scheme and supports service differentiation through prioritised access to the wireless medium. The HCCA works under the control of a hybrid coordinator (HC) and provides a centralised polling scheme. With the HCCA, the QoS-enabled station (QSTA) is able to request specific traffic parameters (data rate, delay, jitter etc.), which allow transmitting multimedia applications more effectively on 802.11 WLANs.

The IEEE 802.11e standard provides a reference design for an HCF scheduler to derive the polling times and periods for different applications. However, the reference scheduler can only allocate a fixed polling schedule, which is unsuitable for VBR video exhibiting burst. It is critical for the 802.11 WLAN to support emerging multimedia applications with QoS guarantees for its successful use in wireless multimedia networking. To the best of the knowledge, there has been little research on MPEG video services over 802.11e HCF, particularly with regard to the QoS feature. Although a few papers [6, 7] have addressed this issue, they have some drawbacks. Grilo *et al.* [6] used a simple earliest deadline first scheduling discipline. Nevertheless, they did not consider the characteristics of MPEG video Ansel *et al.* [7] introduced a fair HCF (FHCF) scheduling scheme that uses queue length estimations to tune the resource allocation for VBR services. However, as explained in Section 2.2, their estimation is based on the unrealistic assumption that the transmission rate of VBR follows a Gaussian distribution, and therefore it cannot accurately predict the required resource.

In this article, an MBDTXOP scheme is proposed that enhances QoS guarantees for VBR video transmission over the 802.11e HCF. The proposed scheme initially allocates a constant bit rate (CBR) bandwidth for a certain part of the VBR video. By employing the self-similar nature of VBR video [2], the CBR bandwidth is predicted on the basis of the past history. The VBR portion of the transmission bandwidth for the remaining part of the video is allocated on demand. Simulation results conducted using real-life MPEG traces show that the proposed scheme significantly outperforms the HCF reference scheduler and the FHCF

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scheme for VBR video transmission in terms of lower latency and higher resource utilisation.

The rest of the article is organised as follows. Section 2 provides an overview of the HCF reference scheduler and the FHCF scheme. Section 3 provides a detailed description of the motivation for this study and the proposed MBDTXOP scheme. The simulation results are presented and discussed in Section 4. Section 5 concludes the article.

2 Related work

2.1 HCF Reference scheduler

To support parameterised QoS, 802.11e defines the HCCA that can operate during both the contention period (CP) and the optional contention-free period, as illustrated in Fig. 1. Controlled access phases (CAPs) are defined as intervals when the HC that usually resided within the QoS-enhanced AP (QAP) controls the medium. The HC can initiate a CAP in the CP after the channel has remained idle for at least a PISF inter-frame space (PIFS) interval by sending a QoS CF-poll frame to allocate HCCA transmission opportunities (TXOPs) to the QSTAs.

The HCCA provides QoS guarantees based on the traffic specification (TSPEC) negotiation between the HC and the QSTAs. Before sending the data, a virtual connection called the traffic stream (TS) is set up. The QSTA sends a set of TSPEC parameters to the HC specifying the QoS requirements for the TS. On receiving this information, the HC decides whether to admit it or not. If it decides to admit the TS, then the HC allocates TXOPs to different TS queues and polls each QSTA according to a scheduling algorithm. A polled QSTA can transmit multiple frames, provided the total access time does not exceed the allocated TXOP.

The 802.11e recommends a simple scheduler that uses the mandatory set of TSPEC parameters to generate a schedule; these parameters are mean data rate, nominal MAC service data unit (MSDU) size and maximum required service interval (SI) (or equivalently, delay bound). The HC divides the beacon interval into SIs of equal length and polls QSTAs on a round-robin basis during each SI. To decide the SI, the HC determines first the minimum value of all the maximum SIs that are required. It chooses the SI as the highest submultiple of the beacon interval, which is inferior to the minimum of all the maximum SIs that are required.

Subsequently, the HC allocates TXOPs to the different admitted TSs. The number of packets arriving in the TS queue j of the QSTA i during one SI is

$$N_i^j = \left\lceil \frac{\rho_i^j \times SI}{L_i^j} \right\rceil \tag{1}$$

where ρ_i^j is the mean data rate and L_i^j is the nominal MSDU size.

Subsequently, the TXOPs, T_i^j, are computed as follows

$$T_i^j = N_i^j \left(\frac{L_i^j}{R} + 2 \times \text{SIFS} + \text{ACK} \right) \tag{2}$$

where R is the physical layer transmission rate, SIFS the short inter-frame space and ACK the time taken to transmit an acknowledgement packet.

Although the reference scheduler is easy to implement, it has some limitations in satisfying the QoS requirements for diverse applications. The reason is that the HC always allocates a fixed amount of TXOPs according to the mean data rate and the average frame size. This is more appropriate for CBR traffic because the bandwidth requirement is fixed and the required bandwidth has to be reserved for a CBR flow at the call setup time. With respect to VBR traffic, this will lead to the low utilisation of the reserved bandwidth or to packet loss (intolerable delay/jitter), as the granted fixed capacity cannot cope with the unexpected increase in the instantaneous bandwidth requirement.

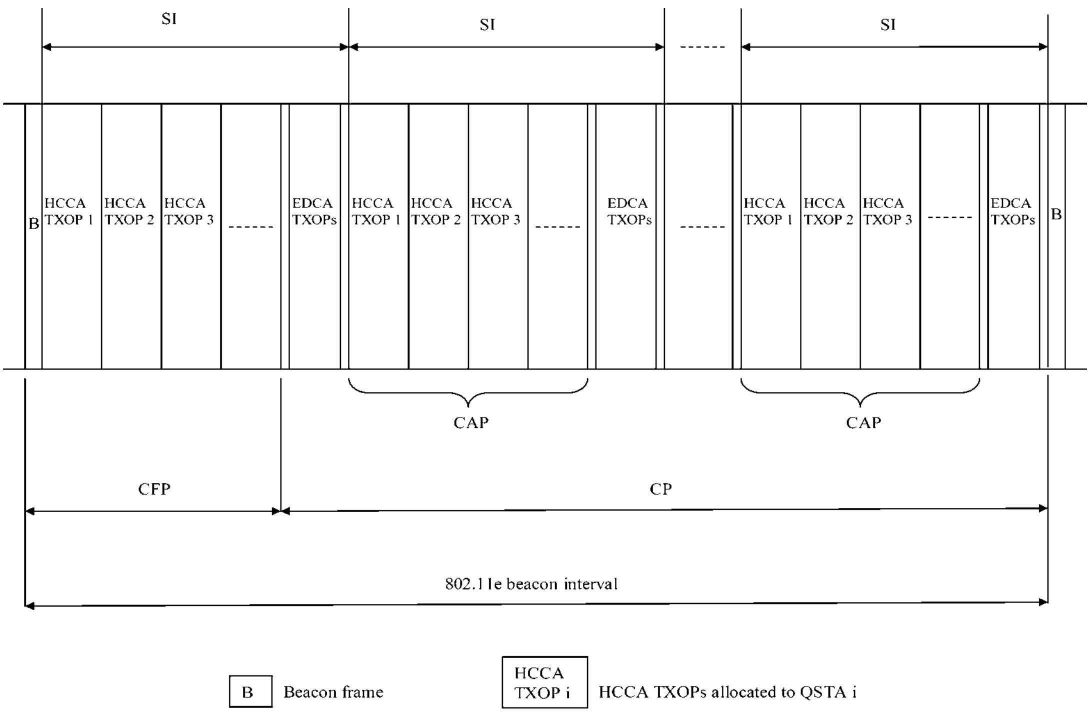

Fig. 1 *TXOPs allocation with the HCF reference scheduler*

2.2 FHCF: a simple and efficient scheduling scheme for IEEE 802.11e WLAN

Basically, the FHCF scheme comprises of two schedulers: the QAP scheduler and the node scheduler. First, the QAP scheduler estimates the varying queue length for each QSTA before the next SI and compares this value with the ideal queue length. The ideal queue length refers to the queue size at the beginning of the next SI, and it is computed according to the average data rate. Secondly, when a QSTA sends a QoS data packet, the QSTA notifies the QAP of its queue length at the end of its TXOP through the header of the packet. Using the queue length information, the QAP scheduler estimates the queue length of the TS at the beginning of the next SI. The QAP scheduler uses a window of previous estimation errors for each TS to compute the estimated queue length. The estimated queue length value equals the sum of the mean arrival rate and the expected value of the absolute deviation. To compute the deviation, the authors assume that the sending rate of a VBR video follows a Gaussian distribution and let the deviation equal the expected value of the estimation errors. Thirdly, the QAP compares the estimated queue length with the ideal queue length at the beginning of the next SI. It computes the number of additional packets, which is the difference between the estimated queue length and the ideal case. Subsequently, the QAP computes the additional required time for each TS to transmit the additional packets and reallocates the corresponding TXOP duration accordingly. The responsibility of the node scheduler located at each QSTA is to redistribute the unused time among its different TSs because a QSTA may have multiple TSs.

3 Motivation and proposed schemes

3.1 Motivation

It is well known that compressed digital video is bursty and is strongly auto-correlated over multiple time scales. Further, recent researches have indicated that the underlying stochastic processes in digital video applications exhibit strong long-range-dependent properties. These characteristics complicate the design of efficient transmission strategies for VBR video as conventional traffic modelling approaches do not accurately estimate the required network resources [8].

To decrease burstiness and the effect of strong long-range dependence for delivering VBR video, many schemes have been proposed. Among these techniques, the most popular is the one in which the so-called video buffer verifier (VBV) [1] is employed as a part of the MPEG encoders. MPEG encoders have one important restriction: the variation in bits per frame is limited. Hence, MPEG defines a hypothetical buffer model – the VBV – that is used to constrain the rate variability that can be generated by an encoder. The VBV is conceptually connected to the output of an MPEG encoder and the input of an MPEG decoder. By monitoring the VBV status, the source rate control algorithm adjusts the quantisation process to ensure that the VBV buffer of the decoder neither overflows nor underflows. Although decreasing the rate variability, this rate-smoothing approach still preserves a certain amount of burstiness in the compressed digital video.

To further decrease the burstiness, some smoothing techniques have been developed to deliver compressed digital videos over networks. Krunz and Tripathi [9] introduced a bandwidth allocation algorithm based on a traffic envelope model that provides a time-varying bound on the bit rate in the video sequence. By using this model, they showed that video sources could be statistically multiplexed with an effective bandwidth, which is often less than the peak rate. Lam *et al.* [10] presented an algorithm for lossless smooth in the video frame rate fluctuations in an MPEG video. The objective of this algorithm is to transmit each video frame with the same pattern at approximately the same rate in addition to ensuring that the buffering delay is bounded for each video frame. The authors in [11] and [12] studied off-line work-ahead smoothing of stored videos. The primary concept in [11] and [12] is to present a large amount of video data to the receiver's buffer before the actual playback time. The video data are delivered at a constant (or piecewise constant) rate over a CBR channel such that the data arrive at the receiver before its display time.

These rate-smoothing techniques are indeed so effective that a number of researchers fail to detect the strong long-range dependence in the rate variation of digital videos. As the VBV model is the normative part of the MPEG standard, any MPEG stream inherently satisfies the VBV requirement. The significant feature of an MPEG video that is encoded using the VBV technique is that the bandwidth demand can be decomposed into a constant bandwidth (DC) component and an additional variable bandwidth (bursty) component that specifies the remaining variability of frame sizes. Both the components are essential and cannot be ignored. On the basis of this decomposition and the strong long-range dependence, an MBDTXOP scheme is proposed to support efficient transmission of compressed digital videos over the 802.11e HCF.

3.2 Measurement-based dynamic transmission opportunity scheme

On the basis of the discussion in the previous section, reserving a certain amount of bandwidth and dynamically allotting bandwidth for the remaining VBR portion should ensure adaptation to the rate variation and improve the QoS for compressed digital video. Accordingly, an MBDTXOP scheme that reserves a certain fraction of the VBR video's average bit rate requirement during the call setup time is proposed. This reserved part (and the corresponding TXOPs) is allocated to the video stream by the HC at each SI. Bandwidth requests for the remaining VBR portion of the video stream are then piggybacked on the transmitted data of the reserved part. The HC will process these piggybacked requests and allocate the corresponding channel capacity for each video stream periodically.

The concept of the proposed scheme can be illustrated by the timing diagram shown in Fig. 2. The first data unit (video frames 1 and 2) and the overhead involved, such as the SIFS and ACK, are larger than the available TXOPs. Here, a portion of the frame [denoted by (1a)] is transmitted in the allotted TXOPs along with a piggybacked request for (1b) and (2). In the next SI, that is, SI 2, the HC will reallocate the TXOPs in response to the piggybacked requests. The fractions (1b) and (2) are then transmitted in the granted bandwidth along with a piggyback request for (3), and the process continues. It should be noted that the QSTA uses the 'queue size' subfield in the QoS control field of the MAC protocol data unit header to send the piggybacked requests.

As the VBR video exhibits significant rate variability, there is still the problem of how to distribute TXOPs in order to guarantee the QoS for a video stream and

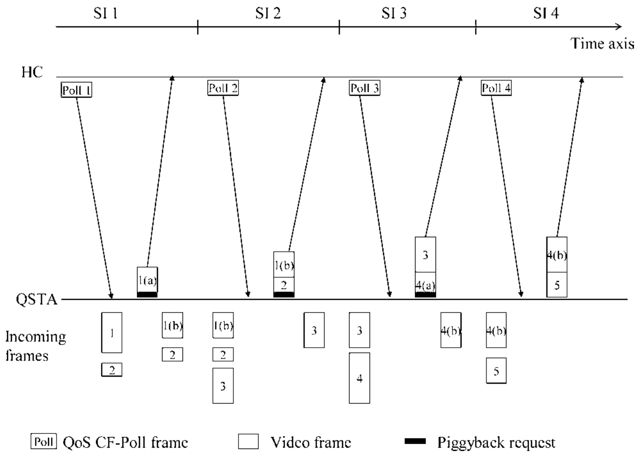

Fig. 2 *Proposed MBDTXOP scheme*

improve the network utilisation. Therefore TXOPs are adjusted dynamically according to TXOPs according to periodic measurements of the following variables: (1) assigned_bw(n), which represents the amount of bandwidth allocated to the video stream during the nth SI (n is the index of SI); (2) unused_bw(n), which indicates the unused portion of the assigned_bw(n) and (3) txop_request(n), which is the amount of traffic demand sent through the piggybacked requests.

At the beginning of each SI, the QAP computes the assigned_bw($n+1$) based on the following equations

$$\text{assigned\_bw}(n+1) = \text{txop\_request}(n) + [\text{assigned\_bw}(n) - \overline{\text{unused\_bw}(n)} + \overline{\text{txop\_request}(n)}] \quad (3)$$

where

$$\overline{\text{unused\_bw}(n)} = \frac{1}{k}\left(\sum_{i=n-k+1}^{n} \text{unused\_bw}(i)\right)$$

$$\overline{\text{txop\_request}(n)} = \frac{1}{k}\left(\sum_{i=n-k+1}^{n} \text{txop\_request}(i)\right)$$

The parameters $\overline{\text{unused\_bw}(n)}$ and $\overline{\text{txop\_request}(n)}$ denote the average values of unused_bw(n) and txop_request(n) in the previous k SIs, respectively. For each video flow, the QAP computes the TXOP($n+1$), which equals the sum of the transmission time of assigned_bw($n+1$) and the associated SIFS and ACK times. It should be noted that an alternative solution that provides better QAP scalability is to request each QSTA performing these measurements and to notify the QAP about the required assigned_bw.

In (3), txop_request(n) signifies the amount of queued data at the end of the nth SI and the term in square brackets represents the estimation of the required bandwidth of the ($n+1$)th SI. It is known that strong long-range dependence and burstiness are inherent qualities of VBR video traffic. Therefore the bandwidth reservation in the current and previous SIs can be used to estimate the bandwidth demand for the next beacon interval.

To illustrate with an example, an MPEG video stream with a 3.6 Mbps average bitrate could be transmitted by initially setting the value of the TXOPs equal to the sum of the amount of time to transmit 2 Mbps data (at a 50 ms SI with a grant size of 50 KB) and the overhead involved and piggybacking requests for the remaining VBR portion of data. Subsequently, the QAP allocates the measurement-based TXOPs.

At the start of each SI, the QAP computes the summation of the measurement-based TXOPs of all the TSs located at the same QSTA and allocates this summation value to each QSTA through polling. By knowing the exact queue information of each TS, the QSTA reallocates the TXOP to each TS after receiving the total granted TXOP. If the total allocated TXOP is greater than the summation of the exact queue sizes of all the TSs, the QSTA transmits all the queued packets of all TSs. However, if the total allocated TXOP is smaller than the summation of the exact queue sizes of all the TSs, the QSTA allocates the TXOP to each TS based on the max–min fairness algorithm [13].

4 Simulation results and discussion

In this section, the performance of the proposed mechanisms with that of the HCF referenced scheduler and FHCF is compared. The proposed MBDTXOP algorithm on an NS-2 HCF simulator is implemented [14] and the module to satisfy our needs is modified For the simulations, the network consists of four QSTAs and a single QAP, in which each QSTA sends a video flow to a common receiver (i.e. the QAP). All the nodes use IEEE 802.11a [15] to communicate at the data and control rates of 54 and 36 Mbps, respectively. The beacon interval is 100 ms and the SI is 50 ms. For video source models, the author has used traces of real MPEG-4 video streams [16]; their properties are listed in Table 1. In particular, it is pointed out that if one adopts the peak-to-average rate ratio as a measure of a video stream's burstiness, 'Silence of the lambs' and 'The firm' could be considered to have the most bursty flows, whereas 'Die hard III' and 'Parking lot cam' have smaller rate variations.

Fig. 3 shows the delay distributions of video streams for MBDTXOP, the FHCF and the HCF referenced scheduler. It should be noted that the delay is the difference between the time at which a video frame is sent to the QSTA's MAC buffer and the time at which it is reassembled from its fragments by the HC. Comparing with Fig. 3*e* with Figs. 3*a* – *d*, it is observed that the delay of the HCF referenced scheduler is too high to satisfy the QoS requirements of digital video, particularly for real-time video transmission. This is because any static allocating bandwidth

Table 1: Traffic properties of video traces

Video traces	Run time, min	Frame rate, frames/s	Mean frame size, bytes	Max frame size, bytes	Mean data rate, bps	Peak data rate, bps	Peak/mean ratio
Silence of the lambs	60	25	2900	22 239	580 K	4.4 M	7.73
The firm	60	25	1500	10 204	290 K	2 M	6.96
Die hard III	60	25	3500	16 960	700 K	3.4 M	4.86
Parking lot cam	60	25	3900	13 851	790 K	2.8 M	3.52

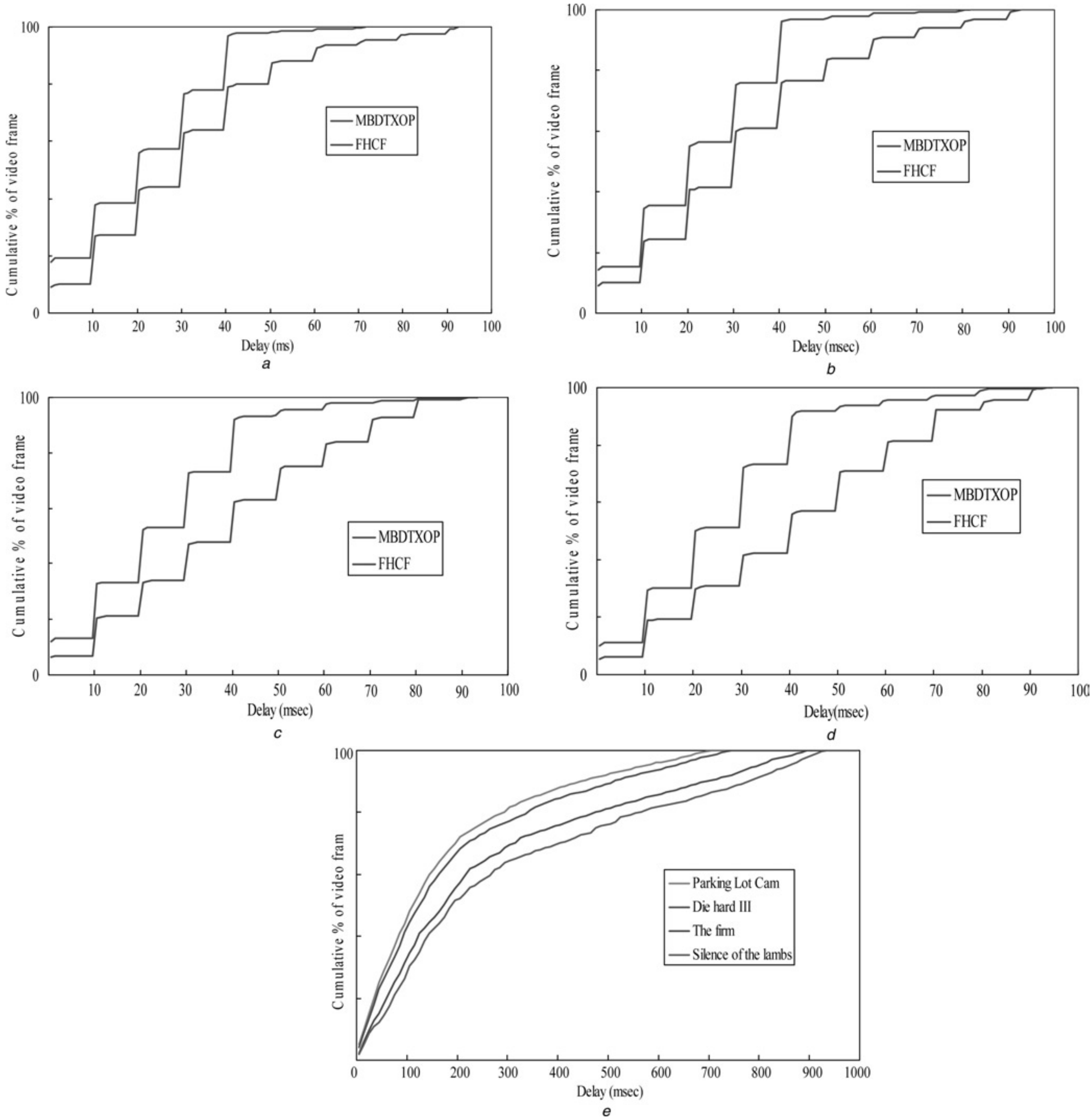

Fig. 3 *Delay distribution of video frames*

a ‘Parking lot cam’ for both the MBDTXOP and FHCF schemes
b ‘Die hard III’ for both the MBDTXOP and FHCF schemes
c ‘Firm’ for both the MBDTXOP and FHCF schemes
d Silence of the lambs for both the MBDTXOP and FHCF schemes
e HCF reference scheduler

for VBR videos would either result in an inefficient utilisation of bandwidth because of over-allocation of the resource or be insufficient to support the required QoS because of the under-allocation of the resource. In contrast, the proposed MBDTXOP scheme and the FHCF scheme use dynamic resource allocation by estimating the future traffic arrival, which is more suitable for VBR video transport. Apparently, the more accurate the traffic estimation, the better the QoS. Further comparing Figs. 3*a* –*d*, it is observed that the MBDTXOP scheme achieves considerably lower latency when compared with the FHCF scheme for all video streams. The reason is that the proposed MBDTXOP scheme is more accurate for capturing the traffic characteristics of MPEG video, such as burstiness and strong long-range dependence. Hence, it is able to adaptively allocate resources to satisfy the QoS requirements of MPEG video transmission. The FHCF scheme impractically assumes that the data rate of VBR video follows a Gaussian distribution, which leads to inaccurate prediction of traffic dynamics. Thus, the FHCF scheme suffers from problems similar to the HCF-referenced scheduler. In other words, if the traffic is underestimated, the desired QoS cannot be guaranteed. In contrast, if the traffic is overestimated, the resource is wasted.

Table 2: Under-allocation ratio and over-allocation ratios for both the MBDTXOP and FHCF schemes

	Under-allocation ratios		Over-allocation ratios	
	MBDTXOP	FHCF	MBDTXOP	FHCF
Silence of the lambs, %	4.76	12.29	5.82	14.63
The firm, %	4.31	13.76	3.94	12.45
Die hard III, %	2.54	7.34	2.88	6.49
Parking lot cam, %	2.29	6.93	2.14	5.38

To delve deeper into the difference in the efficiency between the MBDTXOP and the FHCF schemes, the following performance metrics are defined

$$\text{Bandwidth over-allocation ratio} = \frac{\sum_{\substack{\forall n \\ \text{if assigned\_bw}(n)>q(n)}} [\text{assigned\_bw}(n) - q(n)]}{\text{total required bandwidth for the video stream}} \quad (4)$$

$$\text{Bandwidth under-allocation ratio} = \frac{\sum_{\substack{\forall n \\ \text{if assigned\_bw}(n)<q(n)}} [q(n) - \text{assigned\_bw}(n)]}{\text{total required bandwidth for the video stream}} \quad (5)$$

where $q(n)$ is the buffer occupancy of the video stream at the beginning of the nth SI. It should be noted that in (4) and (5), the numerators represent the total amount of over-allotted and under-allotted bandwidths, respectively. Hence, the bandwidth over-allocation ratio and bandwidth under-allocation ratio indicate the proportion of wasted and deficient resources, respectively. Apparently, a low bandwidth over-allocation ratio means that less amount of bandwidth is wasted and resource utilisation is high. A low bandwidth under-allocation ratio signifies that more bandwidth requests are satisfied and better QoS performance is provided.

Table 2 illustrates the bandwidth over-allocation ratios and bandwidth under-allocation ratios for both the MBDTXOP and FHCF schemes. For all video streams, the MBDTXOP scheme achieves a lower Bandwidth over-allocation ratio and a bandwidth under-allocation ratio when compared with the FHCF scheme. This demonstrates that the MBDTXOP scheme not only supports better QoS performance but also attains higher resource utilisation. Therefore for a given channel capacity, the MBDTXOP scheme can accommodate more VBR streams while preserving the desired QoS of each video stream. Further, this is because the traffic prediction of the MBDTXOP scheme is more accurate when compared with that of the FHCF scheme.

Besides, an interesting phenomenon is observed from Figs. 3*a*–*d* and Table 2 for both the MBDTXOP and FHCF schemes: a less bursty flow experiences a smaller latency, bandwidth over-allocation ratio and bandwidth under-allocation ratio. This suggests that the less bursty the video sample, the smaller will be the prediction error. Therefore the VBR video is more difficult to predict when it is more bursty. The MBDTXOP scheme provides a significantly improved performance with regard to the FHCF scheme as the video trace is more bursty, in terms of the delay, bandwidth over-allocation ratio, and bandwidth under-allocation ratio.

5 Conclusions

In this article, the author has discussed the limitations related to the support of QoS video transmission over the 802.11e HCF and presented in detail the framework of the QoS services of the HCF and simulated its performance for digital videos. On the basis of the observations, a novel MBDTXOP scheme designed for VBR video transmission using the 802.11e HCF is proposed. The unique attribute of the MBDTXOP scheme is that it dynamically allocates resources to VBR video by capturing the traffic characteristics (e.g. burstiness and strong long-range dependence), in contrast to the unrealistic assumptions made by previous proposals. Extensive simulation results using real-life MPEG videos show that MBDTXOP is more accurate in predicting the dynamics of future traffic and provides more efficient traffic regulations, when compared with two existing schedulers – the HCF reference scheduler and the FHCF scheme, thereby leading to low transmission latency. Besides, the MBDTXOP scheme achieves a much more efficient use of the system resources and enables higher bandwidth utilisation when compared with the HCF reference scheduler and the FHCF scheme.

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