

Research Article

Scalable Video Streaming for Single-Hop Wireless Networks Using a Contention-Based Access MAC Protocol

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Limited bandwidth and high packet loss rate pose a serious challenge for video streaming applications over wireless networks. Even when packet loss is not present, the bandwidth fluctuation, as a result of an arbitrary number of active flows in an IEEE 802.11 network, can significantly degrade the video quality. This paper aims to enhance the quality of video streaming applications in wireless home networks via a joint optimization of video layer-allocation technique, admission control algorithm, and medium access control (MAC) protocol. Using an Aloha-like MAC protocol, we propose a novel admission control framework, which can be viewed as an optimization problem that maximizes the average quality of admitted videos, given a specified minimum video quality for each flow. We present some hardness results for the optimization problem under various conditions and propose some heuristic algorithms for finding a good solution. In particular, we show that a simple greedy layer-allocation algorithm can perform reasonably well, although it is typically not optimal. Consequently, we present a more expensive heuristic algorithm that guarantees to approximate the optimal solution within a constant factor. Simulation results demonstrate that our proposed framework can improve the video quality up to 26% as compared to those of the existing approaches.

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1. INTRODUCTION

Recent years have witnessed an explosive growth in multimedia wireless applications such as video streaming and conferencing [1]. One of the reasons for this tremendous growth is the wide deployment of the IEEE 802.11 wireless LANs (WLANs) in both private home and enterprise networks. Despite of these seemingly successes, many fundamental problems of transmitting multimedia data over wireless networks remain relatively unsolved. One of the challenges is how to efficiently guarantee a specified bandwidth for a video flow in a wireless network. The popular WLAN, particularly Distributed Coordination Function (DCF) in typical IEEE 802.11 [2] which operates under a contention-based channel access mechanism, does not provide a mechanism to guarantee minimum bandwidth for multiple concurrent flows. As a result, a video application may experience significant quality degradation due to free admission of an arbitrarily large number of flows. Nevertheless, Point Coordination Function (PCF) in typical IEEE 802.11 and HCF Controlled Channel Access (HCCA) in IEEE 802.11e [3] are able to provide

a polled access mechanism to guarantee the minimum bandwidth. However, to take advantage of PCF and HCCA mechanisms, a scheduler and a queuing mechanism at the AP are needed to control and to regulate the polling frequency in HCCA and PCF to provide flows with the requested throughputs. That said, this paper considers a contention-based approach to admission control, similar to the work of Banchs et al. [4] in which, the parameters of the IEEE 802.11e in the contention-based mode are set appropriately to enable flows to achieve their requested throughputs or reduce the delay.

Admission control prevents a new flow from joining the network in order to maintain a reasonable quality of the existing flows. The decision to admit or reject a new flow that requests to enter a wireline link is arguably easier to make, compared to that of a wireless link. A simple admission control algorithm for a wireline link can keep track of the total used bandwidth. The available bandwidth is then equal to the difference between the link capacity and used bandwidth. A new flow is admitted if its requested bandwidth is smaller than the available bandwidth of the link

by some threshold, otherwise it is rejected. Theoretically, the same algorithm can be applied to a wireless link if a time division multiple access (TDMA) scheme is used to allocate bandwidth for each flow. Using a TDMA scheme, each flow is assigned to a set of exclusive time slots for transmitting its data, thus eliminating the multiuser interference associated with a wireless link. As a result, the admission control algorithm can determine its available bandwidth precisely and make the decision to admit or reject a new flow accordingly.

However, such a protocol may require a centralized scheduling algorithm, which may not be feasible in a distributed environment. Therefore, existing Medium Access Control (MAC) protocols, such as the IEEE 802.11, employ a random access approach that allows the flows to compete for shared channel efficiently. That is, IEEE 802.11 protocol enables the flows to achieve high throughputs, while minimizing their collisions. Thus, characterizing the wasted bandwidth from collisions is specific to a MAC protocol.

The problem of MAC protocols such as the IEEE 802.11 is the multiuser interference, that is, the collisions between the new flow and the existing flows, which reduce all the flow's throughputs. The number of these collisions increases nonlinearly with the number of competing flows, making it harder for an admission control algorithm to determine the resulted throughputs of all the flows in order to make the right decision [5]. In particular, for a simple single-hop wireless network, to decide whether or not to admit a new flow, the admission control algorithm must ensure that the available bandwidth is at least $K + H$ Kbps, where K is the total requested bandwidth including that of the new flow, and H is the incurred overhead from the collisions. While K is given to the algorithm, determining H is nontrivial when using a typical MAC protocol. Computing H is even more difficult in a multihop wireless network.

Even when an algorithm can determine precisely the collision bandwidth, it is not always beneficial to employ the traditional admission control framework in which, the decision to admit a new flow is solely based on the bandwidth and delay requirements of all the flows. Instead, with the advance in video coding techniques, we argue that the criterion for flow admission should be the visual quality of the video streams. That is, the inputs to the admission control algorithm are the minimum visual quality of the video streams, not their bandwidth and delay requirements. The former approach assumes that each video is coded at a certain bit rate, thus any lesser rate provided by the network is unacceptable since the video playback will be interrupted frequently. On the other hand, with scalable video coding techniques, the video is encoded in a layered hierarchy. Thus, a video can be transmitted at different bit rates (or number of video layers), albeit at different visual qualities. The advantage of this approach is that a larger number of flows can be allowed to enter a network as long as the video quality of each flow does not fall below a specified minimum threshold. The objective is then to maximize the average quality of all the admitted videos, given a specified minimum video quality for each stream, and the current available bandwidth.

That said, our paper aims to enhance the quality of video streaming applications in wireless home networks via a joint optimization of video layer-allocation technique, admission control algorithm, and MAC protocol. While it is possible to extend our framework to multihop wireless ad hoc environment, for clarity, our discussion is limited to a one-hop wireless network, for example, the network of all the wireless hosts (devices) within a home or a small building such that every host can hear the transmissions of all other hosts. Using an Aloha-like MAC protocol [6], we present a novel admission control framework, which can be viewed as an optimization problem that maximizes the average quality of admitted videos, given a specified minimum video quality for each flow. In particular, using scalable video streams, our framework allows more flows to enter the network, as long as the video quality of each flow does not fall below a specified minimum threshold. We then present some hardness results for the optimization problem under various conditions and propose two heuristic algorithms for obtaining a good solution. We show that a simple greedy layer-allocation algorithm can perform reasonable well, although it is typically not optimal. Consequently, we present a more expensive heuristic algorithm that guarantees to approximate the optimal solution within a constant factor.

The outline of paper is as follows. We first discuss a few related works on admission control for wireless networks and scalable video coding in Section 2. In Section 3, we describe a MAC protocol to be used in conjunction with the admission control algorithm. We then formulate the admission control framework as an optimization problem in Section 4. In Section 5, we provide some hardness results for the optimization problem, and corresponding heuristic algorithms for obtaining good solutions. Simulation results will be given in Section 6. We then summarize our contributions and conclude our paper with a few remarks in Section 7.

2. RELATED WORK

Providing QoS for flows on the Internet is extremely difficult, if not impossible, due to its original design to scale with large networks. The current design places no limit to the number of flows entering the network, or attempts to regulate the bandwidth of individual flows. As a result, bandwidth of multimedia applications over the Internet often cannot be guaranteed. To that end, many scalable coding techniques have been proposed for video transmission over the Internet. Scalable video coding techniques are employed to compress a video bit stream in a layered hierarchy consisting of a base layer and several enhancement layers [7]. The base layer contributes the most to the visual quality of a video, while the enhancement layers provide successive quality refinements. As such, using a scalable video bit stream, the sender is able to adapt the video bit rate to the current available network bandwidth by sending the base layer and an appropriate number of enhancement layers [8–14]. The receiver is then able to view the video at a certain visual quality, depending on network conditions.

We note that scalable video coding techniques can mitigate the insufficient bandwidth problem, but the fundamental issue is the lack of bandwidth to accommodate all the flows. Thus, admission control must be used. While it is difficult to implement admission control on a large and heterogeneous network, for example, the Internet, it is possible to implement some form of control or regulation in small networks, for example, WLAN. Consequently, there have been many researches on providing some form of QoS for media traffic in WLANs [15–21]. Recently, the introduction of the new medium access control protocol of the IEEE 802.11e called the Hybrid coordination function (HCF); van der Schaar et al. [22] proposed an HCF Controlled Channel Access- (HCCA-) based admission control for video streaming applications that can admit a larger number of stations simultaneously.

Many other existing admission control algorithms for WLANs have also been proposed. Gao et al. [23] provided an admission control by using a physical rate-based scheme in IEEE 802.11e. They use the long-term average physical rates to compute the reservation of the channel for some amount of time called the transmission opportunity (TXOP) for each station then distribute TXOP's to everyone. Their framework provides some certain level of admission control. Xiao and Li [24] used the measurements to provide flow protection (isolation) in the IEEE 802.11e network. Their algorithm is simple, yet effective. The algorithm requires the access point (AP) to broadcast the necessary information to other wireless stations. In particular, the AP announces the budget in terms of the remaining transmission time for each traffic class (there are 4 traffic classes in the IEEE 802.11e) through the beacon frames. When the time budget for a class is depleted, the new streams of this class will not be admitted. Xiao and Li's work set a fixed limit on the transmission time for the entire session, resulting in low bandwidth utilization when every traffic class does not approach its limit. Recently, Bai et al. [25] improved the bandwidth utilization of Xiao and Li's work by dynamically changing the transmission time of each class based on the current traffic condition. There are also other admission control schemes implemented at different layers of the network stack. For example, Barry et al. [26] proposed to monitor the channel using virtual MAC frames and estimate the local service level by measuring virtual frames. Shah et al. [27] proposed an application layer admission control based on MAC layer measurement using data packets. Valaee and Li [28] proposed a service curve based admission procedure using probe packets. Pong and Moors [29] proposed admission control strategy for QoS of flows in IEEE 802.11 by adjusting the contention windows size and the transmission opportunity. All these admission control schemes do not take quality of the traffic, particularly video quality in our framework, into consideration directly. On the other hand, we advocate a direct cross-layer optimization of video quality, admission control algorithm, and MAC protocol, simultaneously. Most similar to our work is that of Banchs et al. [4]. Since we will be using this scheme for performance comparisons, we delay the discussion until Section 6.

3. MAC PROTOCOL

As discussed previously, the amount of wasted bandwidth from collisions in a wireless network is different when using different MAC protocol. In this section, we describe an Aloha-like MAC protocol [6] to be used in the proposed admission control framework that aims at maximizing the average quality of admitted videos, given a specified minimum video quality for each flow. In order to contrast the advantages of the new MAC protocol, we first briefly describe the existing IEEE 802.11e protocols in the contention-based access mode.

3.1. Contention-based access mechanism

The contention-based channel access scheme in existing IEEE 802.11e protocol called Enhanced Distributed Channel Access (EDCA), which defines a set of QoS enhancements for WLAN applications through modifications to the MAC layer. To access the channel, a host first senses the channel. If the channel is idle for more than the Arbitration Interframe Space (AIFS) time, it starts sending the data. Otherwise, it sets a backoff timer for a random number of time slots between $[0, CW_{\min}]$ where CW_{\min} is the minimum contention window size. The backoff timer is decremented by one for each idle time slot after the AIFS time and halts decrementing when a transmission is detected. The decrementing resumes when the channel is sensed idle again for an AIFS time. A host can begin transmission on the channel as soon as its backoff timer reaches zero. If a collision occurs, that is, no acknowledgment packet is received after a short period of time, the backoff timer is chosen randomly between $[0, (CW_{\min} + 1)2^i - 1]$, where i is the number of retransmission attempts. In effect, the contention window size is doubled for each retransmission in order to reduce the traffic in a heavily loaded network. Every time a host obtains the channel successfully, it can reserve the channel for some amount of time (TXOP). Unlike the IEEE 802.11b, IEEE 802.11e can tune the transmission parameters (i.e., CW_{\min} , CW_{\max} , TXOP, AIFS) to provide QoS support for certain applications. The EDCA is able to operate either in ad hoc or infrastructure modes.

The advantage of the existing IEEE 802.11 protocols is that it is bandwidth efficient. That is, based on the current traffic condition, each host adjusts its rate to achieve high throughput while minimizing the number of collisions. On the other hand, the rate of a flow cannot be controlled precisely unless we use PCF or HCCA. Often, this is problematic for video applications. In particular, without using PCF or HCCA, the fluctuation in achievable throughput would likely occur in the existing IEEE 802.11 protocols due to their best effort behaviors. However, PCF and HCCA require to have such a perfect scheduler in order to guarantee the achievable throughputs of all the flows. Thus, we argue for a different MAC protocol which, when used, would produce a stable throughput for a flow. Furthermore, it is preferable to implement the new MAC protocol with minimal hardware modification to the existing IEEE 802.11 devices. Indeed, this is possible.

3.2. Proposed MAC protocol

In the new MAC protocol, the contention window size is not doubled after every unsuccessful retransmission attempt. Instead, depending on the rate requested by a host, it is assigned to a fixed value. All other operations are exactly identical to those of the IEEE 802.11 protocol. We argue that when a proper admission control is employed, eliminating the doubling of CW in the IEEE 802.11 protocol helps to increase the bandwidth efficiency since the rate of each host is not reduced unnecessarily. We note that the existing works with EDCA cannot precisely control the rate due to best effort behavior. Furthermore, the transmission parameters (i.e., CW_{\min} , CW_{\max} , TXOP, AIFS) in EDCA are not designed to achieve the exact rate (on average). This would result in unnecessarily increasing in either the transmission rate comparing to requested rate or unexpected collision. However, our proposed protocol is able to solve such problems in contention based IEEE 802.11e.

Based on the above discussion, it is crucial for an admission control algorithm to determine whether or not there exists a set of CWs for each host that satisfies their requested rates without doubling CWs. To answer this question, we now proceed with an analysis of the new MAC protocol.

We assume the use of reservation packets, that is, Request-To-Send/Clear-To-Send (RTS/CTS) packets. RTS/CTS packets are employed to reduce the collision traffic as well as eliminating the hidden terminal problem [30]. The main idea is to send small packets to reserve the channel for the actual data transmission. By doing so, collisions only occur with the small packets, hence reducing the amount of wasted bandwidth. Since we assume that all the hosts can hear each other's transmissions, we do not have the hidden terminal problem. Our use of RTS/CTS is simply to reduce the collision bandwidth.

Our analysis is based on time-slotted, reservation-based protocols similar to the Aloha protocol, where the time taken to make a reservation is a geometrically distributed random variable with parameter p . The significant difference between our protocol and the Aloha protocol is that all the hosts in our network are assumed to be able to hear each other transmissions. Therefore, a host will not attempt to transmit if it determines that the channel is busy, that is, some host is sending. Thus, a host will attempt to send an RTS packet with probability p only if it determines that the channel is idle.

Assume the host transmits the packets with some probability p . To translate the transmission probability p back to the contention window size used in IEEE 802.11 protocol, CW can be set to $2/p$. We note that this is only an approximation since CW in the IEEE 802.11 protocol is not reset at every time slot. To simplify the analysis, we further assume that every host can start at most one flow at any point in time. A straightforward generalization to support multiple flows per host is to consider all the flows from one host as one single large flow with the transmission probability p . Whenever a host successfully obtains the channel, it selects a packet from one of its flows to send. The probability of a packet selected from a particular flow then equals the ratio

of that flow's throughput to the total throughput of all the flows on the same host. This approach would result in the correct average required throughputs for all the flows.

For a network with N flows, our objective is to determine whether or not there exists a set of p_1, p_2, \dots, p_N and for each flow such that all the flows achieve their specified throughputs R_1, R_2, \dots, R_N , taking into account collisions. Since the rates R_i 's depend on the percentages of successful slots, we first characterize the percentages of collided, successful, and idle slots, given p_i 's for each flow i . To that end, let us denote the following:

- (i) I : percentage of idle slots,
- (ii) S_i : percentage of successful RTS slots for a flow i ,
- (iii) C : percentage of collided slots,
- (iv) R_i' : throughput of flow i as a fraction of the channel capacity.

Note that $I + C + \sum_i S_i = 1$. Suppose the transmission probability for a new flow is p , then for C -type slots, in which collisions occur, the new traffic would have no impact on it. For S -type slots, with probability p , it may cause a collision. For an I -type slots, with probability p , it would become a S -type slot. Otherwise it stays the same. Using the above argument, we can calculate I , S , and C after the new flow starts. In particular, the new idle, collided, and successful probabilities can be calculated using the current I , C , S , and p as

$$\begin{aligned} S_{\text{new}} &= S_{\text{current}}(1 - p) + I_{\text{current}}p, \\ I_{\text{new}} &= I_{\text{current}} - I_{\text{current}}p, \\ C_{\text{new}} &= 1 - I_{\text{new}} - S_{\text{new}}. \end{aligned} \quad (1)$$

Here, we denote $S = \sum_i S_i$. Similarly, we can calculate the successful probability S_i as

$$S_{i,\text{new}} = S_{i,\text{current}}(1 - p), \quad (2)$$

for any existing flow i , and the successful probability for the new flow (S_{N+1}) as

$$S_{N+1} = I_{\text{current}}p. \quad (3)$$

Using the equations above, one can compute the I 's, C 's, and S_i 's for N flows, given the transmission probabilities p_1, p_2, \dots, p_N . In particular, the following algorithm can be used to compute the collision probability C , which will be used in the admission control algorithm later.

Algorithm 1 enables us to compute the successful probability precisely based on the given transmission probabilities p_i 's. On the other hand, one typically wants to determine the transmission probabilities p_i 's, given the requested rates R_i 's from each flow i . Since the rate R_i' is proportional to the corresponding successful probability S_i , we now show how to compute p_i 's based on S_i 's. We then show how to relate S_i 's to R_i 's, completing our objective.

In principle, (1)–(3) enable us to write down a set of N equations with N unknown variables p_1, p_2, \dots, p_N in terms of the known variables S_i 's, and solve for p_i 's. Unfortunately,

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C = Compute_C( $p_1, p_2, \dots, p_N, N$ )
I = 1
C = 0
S = 0
for  $i = 1$  to  $N$  do
   $S = S \times (1 - p_i) + I \times p_i$ 
   $I = I - I \times p_i$ 
   $C = 1 - I - S$ 
end for
return C

```

ALGORITHM 1: Computing C , given the transmission probabilities p_i 's.

these equations are not linear, and therefore difficult to solve. We propose an algorithm to find the p_i 's given S_i 's based on the following observation. When a flow i stops, I will increase by S_i . If flow i starts again with the same transmission probability p_i as before, its successful probability remains S_i as before. Hence, the following equations hold:

$$(I + S_i)p_i = S_i, \quad p_i = \frac{S_i}{I + S_i}. \quad (4)$$

This is true because $I + S_i$ is the probability of idle slots without flow i . Hence, after the flow i starts, its successful probability is $(I + S_i)p_i$ which should also equal precisely to S_i , the successful probability before it stops. Thus, we have N such equations corresponding to N flows. We also have the constraint

$$I + C + S = 1, \quad (5)$$

where C and S are the collision and successful probabilities for all the flows. We note that I is the same for every equation since it is the probability of idle slots when all flows are active. Now, we can solve for $N + 1$ unknowns, that is, N for p_i 's and one for I . Solving this set of $N + 1$ equations is simple since each equation is linear except (5). Equation (5) is nonlinear in p_i because C and S are polynomials in p_i which are the results from (1)–(3). However, (5) will be used as a constraint. Since $I \in [0, 1]$, one can systematically try different values of I from large to small, that is, 1 to 0. For each value of I , we compute p_i 's according to (4). All the p_i 's are then input to Algorithm 1 to compute C . We then test to see whether or not $I + C + S$ approximately equals 1. If so, we have an admissible set of solutions. If not, we increase I by a small value and repeat the procedure. If the algorithm cannot find such I for the entire range of $I \in [0, 1]$, then the solution does not exist. This indicates invalid S_i 's.

Typically, R_i 's, not S_i 's, are given. Therefore, to use the procedure above, we first calculate the S_i 's in terms of R_i 's. With minimal modification from IEEE 802.11e standard, our framework uses IEEE 802.11e frame formats and the timing diagram as shown in Figure 1. After the channel is idle for a period time equal to a distributed interframe space (DIFS) time slots, instead of counting down CW before beginning a new transmission, the host sends RTS with probability p

to reserve the shared channel. That means we set AIFS = DIFS as same as the one in typical IEEE 802.11 standard [2]. Because all hosts can listen to each other transmissions, the collision RTS will occur only if there is more than one host initiating RTS's at exactly the same time slot. Otherwise, the host successfully reserves the channel, then that host can begin the transmission for TXOP time slots without further collision. A host detects unsuccessful transmission of an RTS if none of the CTS arrives within DIFS time slots. Note that a host needs to wait for a short period of time called Short Interframe Space (SIFS) where $SIFS < DIFS$ before sending an ACK as shown in Figure 1. To be fair among all the flows with the same traffic class [3], that is, video streams, everyone uses the same TXOP where $TXOP = CTS + PHY_{hdr} + MAC_{hdr} + PAYLOAD + ACK + 3SIFS + DIFS$.

Suppose after T time slots where T is large, we observe that there are K_i successful transmissions of RTS and $K_i \times TXOP$ slots of data transmission for each flow i . Then by definition, we have

$$\begin{aligned} S_i &= \frac{K_i}{T - \sum_{i=1}^N K_i \times TXOP} \\ &= \frac{K_i \times TXOP/T}{TXOP \times \left(1 - \sum_{i=1}^N K_i \times TXOP/T\right)} \\ &= \frac{R'_i}{TXOP \times \left(1 - \sum_{i=1}^N R'_i\right)}, \end{aligned} \quad (6)$$

where $R'_i = K_i \times TXOP/T$ can be thought of as the host i 's requested bandwidth in terms of a fraction of the channel capacity, and N is the number of flows. If the channel capacity is BW , then the transmission rate R_i can be computed such that $R_i = R'_i \times BW$. For example, if channel capacity (BW) is 54 Mbps, and host i requests the rate (R_i) of 27 Mbps, then $R'_i = 0.5$.

Using (6), given the specified rates R'_i 's, one can compute the corresponding S_i 's, which are then used in the following algorithm to determine the transmission probabilities p_i 's, if there are such p_i 's.

We note that for each unsuccessful RTS transmission, we waste the channel equal to $RTS + DIFS$ time slots. On the other hand, each successful RTS transmission uses only RTS time slots. Furthermore, Algorithm 2 explicitly considers the percentage of collided, successful, and idle slots with respect to RTS transmissions to reserve the channel. This results in $total = I' + C(RTS + DIFS) + \sum_{i=1}^N S_i(RTS)$ where $total$ is close to (or equal to) 1. We now describe our proposed admission control framework.

4. ADMISSION CONTROL FRAMEWORK

4.1. Architecture

Due to a typical small size of a single-hop network, our admission control algorithm runs at the AP or an elected host. We assume that all hosts are collaborative. That is, each host obeys the admission protocol which operates as follows.

For simplicity, in this paper, we assume that there is no cross-traffic of any kinds except videos. In general, to

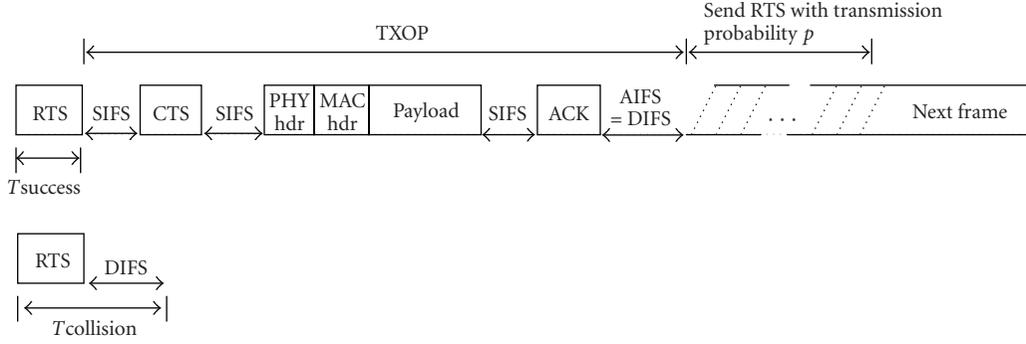


FIGURE 1: Timing diagram with RTS/CTS for our proposed framework.

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[ $p_1, p_2, \dots, p_N, \text{success}$ ] = Compute_ $p(R'_1, R'_2, \dots, R'_N, N)$ 
 $\epsilon = 0.01$ 
 $I' = 1$ 
{ $I'$  is the percentage of idle slots}
search_step = 0.01
success = 0
for  $i = 1$  to  $N$  do
     $S_i = \frac{R'_i}{\text{TXOP} \times (1 - \sum_{i=1}^N R'_i)}$ 
end for
while  $I' < 1$  do
    for  $i = 1$  to  $N$  do
         $p_i = \frac{S_i}{I' + S_i}$ 
    end for
    {run Algorithm 1 to compute collision probability  $C$ }
     $C = \text{Compute}_C(p_1, p_2, \dots, p_N, N)$ 
    total =  $I' + C(\text{RTS} + \text{DIFS}) + \sum_{i=1}^N S_i(\text{RTS})$ 
    {check for boundary condition smaller  $\epsilon$  results in higher accuracy}
    if (abs(total - 1) <  $\epsilon$ ) then
        success = 1
        return [ $p_1, p_2, \dots, p_N, \text{success}$ ]
    end if
     $I' = I' - \text{search\_step}$ 
end while {fail to find  $p$ , success = 0}
return [0, 0, ..., 0, success]

```

ALGORITHM 2: Compute p_i 's given all R'_i 's.

accommodate other nontime sensitive traffic in the proposed framework, one can perhaps set the minimal throughput requirements for the traffic. Each host can send videos to and receive from the Internet, or they can send videos among each other. When a host wants to inject a new video stream into the network, it first requests to join the network by sending a message to the AP. For video streaming applications, the message may contain the rate distortion profile of the video, which specifies the different distortion amounts and the corresponding number of layers used. The message also contains the maximum allowable distortion for a video. Note that for live video applications, the rate-distortion profile is typically not known ahead of time, but

can be estimated. That said, the focus of this paper will be on streaming applications. Upon receiving the request, the AP (or some elected host) will run the admission control algorithm to produce a set transmission probabilities p_i 's for each flow i that maximizes the average visual quality of all the flows, given the maximum distortion levels for each video and overall bandwidth constraint. If such transmission probabilities exist, the AP will broadcast the transmission probabilities p_i 's to all the hosts.

Upon receiving AP's instructions, each host i begins to transmit its packets with probability p_i (or roughly setting its contention window to $2/p_i$) when it observes that the channel is idle. Each transmission probability p_i corresponds

to a particular rate (or number of layers). If there is no feasible set of transmission probabilities, the AP will inform the new flow that it cannot join the network at this moment.

4.2. Problem formulation

We are now at the position to formulate a rate-distortion optimization problem for multiple layered video streams under bandwidth and distortion constraints. We note that the average throughput per unit time or transmission rate R_i for a flow i can be achieved by setting its transmission probability p_i . When there is enough bandwidth for everyone, p_i 's are set to large values so that all the layers of all the video streams would be sent. When there is not enough bandwidth, for example, due to too many flows, the layers from certain videos are dropped resulting in the least average distortion over all the videos. For a simple scenario, we assume that there is no packet loss during transmission. The transmission rate $R_i(l_i)$ for flow i is proportional to the number of transmitted video layers l_i .

The optimization problem studied in this paper is to select the optimal number of video layers to transmit for each of N hosts (or N flows) while maximizing the overall video quality. Furthermore, the inclusion of the bandwidth overhead term $H = C + S$ due to channel contention access (collision and reservation bandwidth used for RTS/CTS packets) makes our optimization problem distinct from other optimization problems. In particular, the problem is specified by giving: for each host, a function $D_i(l_i)$, that gives the reduction in distortion when using l_i layers at host i , a rate function $R_i(l_i)$ that gives the required bandwidth for transmitting l_i layers from host i , an overhead function $H(l_1, \dots, l_N)$ that gives the amount of bandwidth consumed by overhead (e.g., due to the channel contention) for a given assignment of layers to hosts, lower bounds on the reduction in distortion for each i denoted by Z_i , and finally a bound on the total bandwidth BW. Given these quantities, the optimization problem is as follows:

$$\begin{aligned} & \text{maximize} && \sum_{i=1}^N D_i(l_i) \\ & \text{over} && l_i \\ & \text{subject to} && D_i(l_i) \geq Z_i, \\ & && \sum_{i=1}^N R_i(l_i) + H(l_1, \dots, l_N) \leq \text{BW}. \end{aligned} \quad (7)$$

That is, we must find the optimal assignment of layers to each host that maximizes the reduction in total distortion subject to bandwidth and local minimum reduction in distortion constraints. In particular, there exists a solution if we are able to compute a set of transmission probabilities p_i 's corresponding to an optimal assignment of layers for everyone. A necessary condition is that each flow i is required to maximize its total reduction in distortion D_i at least Z_i . Nevertheless, the way to select the layer depends on what layer-selection strategies we use (e.g., greedy algorithm, exhaustive search). Note that propagation delay and processing delay can be negligible due to operating in a single-hop

network. However, the delay variation or jitter would likely affect the performance of the protocol. The detail analysis of throughput jitter is discussed in Section 6.3. Next, we will study the computational properties of the layer-selection problem and show that while in general the problem is computationally hard, under certain reasonable conditions, a simple greedy layer-allocation algorithm can be guaranteed to perform close to optimal.

5. COMPUTATIONAL COMPLEXITY OF LAYER OPTIMIZATION

In this section, we study the computational complexity of the layer allocation problem described above, showing both hardness results and conditions under which optimal and approximate solutions can be guaranteed in polynomial time. Our optimization problem is distinct from most other bandwidth optimization problems by its inclusion of the overhead term H in the bandwidth constraint. Thus, existing algorithms and complexity proofs do not directly apply to our problem. Below, we first consider the complexity of solving the problem optimally, and then we consider efficient approximation algorithms.

5.1. Computing optimal solutions

Here, we analyze the computational complexity of problem classes with the form given in the previous section. We begin by stating three assumptions about the optimization problem and consider the complexity under various subsets of these assumptions.

Assumption 1. Uniform rate increase per level:

$$R_i(l+1) - R_i(l) = R_j(l'+1) - R_j(l'), \quad \text{for any } i, j, l, l'. \quad (8)$$

Assumption 2. Diminishing returns:

$$D_i(l+1) - D_i(l) \leq D_i(l) - D_i(l-1), \quad \text{for any } i, l. \quad (9)$$

Assumption 3. Invariant overhead:

$$H(\dots, l_i+1, \dots) = H(\dots, l_j+1, \dots), \quad \text{for any } l_1, \dots, l_N. \quad (10)$$

Below, we will also refer to the property of additive overhead which means that $H(l_1, \dots, l_N)$ can be factored as a sum of the individual overhead function H_i . That is,

$$H(l_1, \dots, l_N) = \sum_{i=1}^N H_i(l_i). \quad (11)$$

Intuitively, the first assumption states that the amount by which the rate function increases is constant across all layers of all streams. The second assumption states that within a particular stream, higher layers may never reduce distortion more than the lower layers. Thus, it will never be the case that a stream must include many lower layers with low distortion reduction in order to get a big distortion

reduction at a higher layer. The third assumption states that, given a particular layer allocation across layers, incrementing any layer by one produces the same increase in the overhead function. This means that the overhead function is impartial to both the particular stream that is incremented and the current number of layers allocated to that stream.

Our first result is that given the above three assumptions (8)–(10), we can solve the optimization problem using an efficient greedy layer-allocation algorithm. The algorithm proceeds as follows.

- (1) For each stream i , we initialize the layer count l_i to the smallest l_i such that $D_i(l_i) \geq Z_i$. If for some i this is not possible, then return “no solution.”
- (2) If it is not possible to increment the layer count of any stream without violating the bandwidth constraints then terminate and return the current layer counts. In other words, it is not possible to find a feasible set of transmission probabilities for each host using the Algorithm 2 in Section 3.
- (3) Increment the layer count of stream i by 1, where stream i is the stream that when incremented produces the greatest reduction in distortion without violating bandwidth constraints.

Proposition 1. *The greedy layer-allocation algorithm is optimal for any problem where Assumptions 1, 2, and 3 hold.*

Proof. We first introduce some notation. We will use an allocation vector $L = \langle l_1, \dots, l_N \rangle$ to specify the layer allocation l_i to each host i where N is the total number of hosts. We will denote by $D(L)$ the reduction in distortion resulting from allocation vector L . A layer increment sequence is a sequence of host indices (i_1, \dots, i_k) , indicating the order of layers to increment finally arriving at a final allocation vector where k is the total increments in layers.

Note that with invariant overhead and uniform rate increase, each increment in the layer counts results in exactly the same increase in bandwidth. This means that all optimal layer allocations will satisfy $\sum_i l_i = k$ for some value k . That is, all optimal layer allocations will be a result of exactly k increments to layer counts. Thus, finding the optimal layer allocation is equivalent to finding a length k layer increment sequence that results in the best layer allocation starting from the null allocation.

Now, consider any layer allocation L and let i^* be the index of the host that would be selected by the greedy algorithm starting from L , and let Δ^* be the reduction in distortion resulting from the greedy step. Now consider any layer increment sequence (i_1, \dots, i_ν) starting at L resulting in an allocation vector L_ν . We say that the sequence is an optimal ν -step completion of L if the value of $D(L_\nu)$ is the maximum possible when starting from L and incrementing ν layers.

Our key claim is that there is always an optimal ν -step completion to L that includes an increment to i^* . Assume that this was not the case and that the above sequence was an optimal completion, implying that it does not contain an

increment to i^* . We show that this leads to a contradiction. First, let Δ_j equal the reduction in distortion resulting after adding the j th layer increment, and note that $D(L_\nu)$ is equal to the sum of this sequence. By the diminishing returns assumption, we have that $\Delta^* \geq \Delta_j$ for all j . This is true because the greedy algorithm selected the index i^* with the largest decrease in distortion across all layers and thus any further decreases resulting from incrementing any layer must not be greater than that, otherwise this would violate diminishing returns. Given this fact consider the new layer increment sequence $(i^*, i_1, \dots, i_{\nu-1})$ and let L^* equal the result of applying this sequence starting at L . It can be easily verified that this is a legal sequence, and that the corresponding sequence of reductions in distortion is equal to $(\Delta^*, \Delta_1, \dots, \Delta_{\nu-1})$. Since $D(L^*)$ is simply the sum of this sequence and we know that $\Delta^* \geq \Delta_\nu$ this implies $D(L^*) \geq D(L_\nu)$. Thus, we have shown an optimal k -step completion that includes an increment to i^* , which gives a contradiction.

Using the above fact, it is straightforward to show by induction on the number of greedy steps k that the greedy algorithm always maintains an optimal k -step completion of the null set, which completes the proof. \square

We now consider in Propositions 2–4, the complexity of this problem when each one of the above assumptions is lifted.

Proposition 2. *The class of decision problems for which Assumptions 2 and 3 hold but Assumption 1 does not is NP-complete even if one restricts the overhead to be the constant zero function.*

Proof. Our problem is clearly in NP, as it is possible to enumerate possible layer allocations and check them in polynomial time. Each layer-allocation certificate is polynomial-size implying that the decision problem is in NP. To show NP-hardness, we reduce from 0-1 knapsack problem. More formally, an instance of 0-1 knapsack is a 4-tuple as shown in

$$\langle \{v_1, \dots, v_N\}, \{c_1, \dots, c_N\}, V, C \rangle, \quad (12)$$

where v_i and c_i , and give the value and cost of the i th item, V is the value goal, and C is the cost limit. We will form the following version of our problem as in

$$\langle \{1, \dots, 1\}, \{D_1(l_1), \dots, D_N(l_N)\}, \{R_1(l_1), \dots, R_N(l_N)\}, \\ H(l_1, \dots, l_N), V, C \rangle, \quad (13)$$

where $D_i(l_i) = v_i$, $R_i(l_i) = c_i$, and $H(l_1, \dots, l_N) = 0$ for all inputs. That is, we have only one layer to allocate. The reduction in distortion and the rate function for that layer are equal to v_i and c_i of the 0-1 knapsack problem, respectively. Note that this problem does not satisfy the constant rate increase since c_i can be different for each i . However, it does satisfy Assumptions 2 and 3 trivially. It is straightforward to show that the answer to the layer-allocation problem given by (13) will be “yes” if and only if the answer is “yes” for the corresponding 0-1 knapsack problem. \square

Proposition 3. *The class of problems for which Assumptions 1 and 3 hold but Assumption 2 does not is NP-complete even if one restricts the overhead to be the constant zero function.*

Proof. The problem is in NP for the same reasons as above. For the purposes of this problem, we will only consider the 0-1 knapsack problem with integer values of v_i , c_i , V , and C . We can do this without loss of generality since we can always multiply all numbers by the appropriate power of 10. Given an instance of the 0-1 knapsack problem as specified in (12), our reduction constructs the following layer allocation problem:

$$\langle \{c_1, \dots, c_N\}, \{D_1(l_1), \dots, D_N(l_N)\}, \{R_1(l_1), \dots, R_N(l_N)\}, \\ H(l_1, \dots, l_N), V, C \rangle, \quad (14)$$

where $D_i(l_i) = 0$ for $l_i < c_i$, $D_i(c_i) = v_i$, $R_i(l_i) = l_i$, and $H(l_1, \dots, l_N) = 0$. The intuition here is that we have many layers in each stream, but only the last layer actually reduces the distortion. This type of behavior violates Assumption 2. Each layer adds exactly one unit of bandwidth which satisfies Assumption 1 and the overhead is zero, which satisfies Assumption 3. Note also that the number of layers for flow i is c_i . So in order to get a reduction in distortion of v_i , we must pay a bandwidth of c_i , which aligns with the 0-1 knapsack problem.

Given this reduction, it shows that there is a “yes” answer for the constructed layer allocation problem if there is a “yes” answer for the 0-1 knapsack instance. \square

Finally, we show that Assumption 3 is also necessary in some sense. In particular, when it is lifted the problem becomes computationally hard even when restricted to the class of problems with additive overhead.

Proposition 4. *The class of problems for which Assumptions 1 and 2 hold but Assumption 3 does not is NP-complete even if one restricts to additive overhead.*

Proof. Again here we will only consider the integer knapsack problem. Given an instance of an integer 0-1 knapsack problem, we construct the following instance of the layer allocation problem:

$$\langle \{v_1, \dots, v_N\}, \{D_1(l_1), \dots, D_N(l_N)\}, \{R_1(l_1), \dots, R_N(l_N)\}, \\ H(l_1, \dots, l_N), V, C \rangle, \quad (15)$$

where $D_i(l_i) = l_i$, $R_i(l_i) = 0$, and $H(l_1, \dots, l_N) = \sum_i H_i(l_i)$, where $H_i(l_i) = c_i$ for $l_i > 0$ and $H_i(0) = 0$. So here we have the diminishing return property since for each layer we add a single unit of reduction in distortion. We have the constant bandwidth property trivially. But we do not have invariant overhead since when we move a layer l_i from 0 to 1 we get an increase in c_i . Only the overhead function occupies the bandwidth since all the rates are equal to zero. Given this reduction, it is easy to verify that there is a “yes” answer to the 0-1 knapsack instance if there is a “yes” answer to the constructed layer allocation problem. \square

Together these complexity results show that if we remove any one of three assumptions, the problem becomes NP-hard and hence is not likely to be solved by an efficient algorithm, in particular the greedy algorithm. The results also show that this is true even if we place strict restrictions on the form of the overhead function. Even if the overhead is additive, the problem is hard as shown by Proposition 4.

In practice, it may often be possible to satisfy Assumptions 1 and 2. Unfortunately, we can show that the overhead function arising in our protocol is not invariant as required by Assumption 3, and hence an efficient optimal solution is still unlikely.

Proposition 5. *The overhead of the proposed MAC protocol is not invariant.*

Proof. We will show that the overhead of proposed MAC protocol is not invariant by contradiction. Assuming that the bandwidth overhead $H = C + S$, bandwidth involved in reservation, is invariant, then

$$H'(i) = H'(j), \quad (16)$$

where $H'(i)$ and $H'(j)$ denote the overhead resulted from adding δ bps (one layer) into flow i and flow j , respectively. Since $I + C + S = I + H = 1$, we have

$$I'(i) = I'(j), \quad (17)$$

where $I'(i)$ and $I'(j)$ denote the idle slots resulted from adding δ bps into flow i and flow j , respectively. In particular, adding δ bps into flow i results in the increase of S_i by Δ . We can represent I in terms of S_i as

$$I = \prod_i (1 - p_i) = \prod_i \left(1 - \frac{S_i}{I + S_i}\right) = \prod_i \left(\frac{I}{I + S_i}\right). \quad (18)$$

That is,

$$\left(\frac{I'(i)}{I'(i) + (S_i + \Delta)}\right) \prod_{k \neq i} \left(\frac{I'(i)}{I'(i) + S_k}\right) \\ = \left(\frac{I'(j)}{I'(j) + (S_j + \Delta)}\right) \prod_{k \neq j} \left(\frac{I'(j)}{I'(j) + S_k}\right). \quad (19)$$

Expanding the product on both sides of (19), all product terms, except the one with either S_i or S_j , will be canceled out, leading to

$$(I'(i) + (S_i + \Delta))(I'(i) + S_j) = (I'(j) + S_i)(I'(j) + (S_j + \Delta)). \quad (20)$$

Since $I'(i) = I'(j)$, (20) is true if $S_i = S_j$. Since S_i is directly proportional to R_i , this implies that in order to achieve $H'(i) = H'(j)$, the current sending rate of any two video stream must be equal to each other. This is not true in general, therefore the bandwidth overhead of the proposed MAC protocol is not invariant. \square

5.2. Computing approximate solutions

Of the three assumptions above, Assumption 2, diminishing returns, is the one that is most likely to be satisfied in

application settings, since most coding schemes exhibit diminishing returns behavior. Assumption 1, uniform rate increase, will also often be satisfied, though it will rule out nonuniform rate coding schemes. Assumption 3, invariant overhead, as we have seen is violated by our protocol and we are unaware of other protocols that satisfy the assumption. In this light, it is interesting to consider what can be said theoretically when only Assumption 2 is satisfied. We know from Propositions 2 and 3 that in general the problem is NP-hard to solve optimally with only Assumption 2, however, this does not rule out the existence of efficient approximation algorithms.

In fact, using a slight modified the greedy layer-allocation algorithm, we can obtain a solution guaranteed within a factor of $(1 - e^{-1}) \geq 0.63$ from the optimal solution. We now describe the first approximate algorithm.

5.2.1. Double-greedy algorithm

This algorithm is based on the recent result in [31]. We consider a modified version of the original greedy algorithm, where at each step instead of adding the video layer x that most increases in the reduction in distortion, we add the layer that achieves the largest ratio of the reduction in distortion to the increases in bandwidth, provided that adding x does not violate the total bandwidth constraint BW. That is, for each iteration, we add the layer x with maximum ratio of the reduction in distortion to the increases in bandwidth, such that the total usage bandwidth is less than BW. The iteration repeats until no video layer can be added to the network without violating the bandwidth constraint. Thus, it can be shown that even this modified algorithm can yield arbitrarily poor results compared to the optimal solution. However, if one returns the best solution found by either the original greedy algorithm or the modified greedy algorithm, then one can guarantee an approximation factor of $0.5(1 - e^{-1})$. We will call this algorithm the *double-greedy algorithm*.

This shows that by increasing the computation time by a factor of two over the original greedy algorithm (i.e., we must now run both greedy and modified greedy), it is possible to achieve a nontrivial approximation bound. (Technically, it is not necessary to run the full greedy algorithm in order to achieve the approximation bound. Rather, one needs to only run the original greedy algorithm for one iteration (i.e., selecting the best single element of the set) and then to return the maximum of the best single element and the result of the modified greedy algorithm. The results of *double-greedy* are guaranteed to be at least as good as this and often better, but with an increase in computation time.)

5.2.2. Triple-greedy algorithm

It turns out that by increasing the computation further, but remaining polynomial time, it is possible to improve the approximation bound to $(1 - e^{-1})$ for the constrained optimization problem, which matches the result for the unconstrained problem, as proven in [31, 32]. The new algorithm simply enumerates all triples of consecutive layers, denoted by T , in each flow that do not violate the bandwidth

constraint BW. For each triple T , the algorithm runs the modified greedy algorithm initialized to the set T then returns the set T' among all of the triples that achieved the highest ratio of the reduction in distortion to the increases in bandwidth. This algorithm increases the runtime by a factor of $O(|E|^3)$ over the original greedy algorithm, but yields a much stronger approximation result. We have the following result.

Theorem 1. *The double-greedy* and triple-greedy* algorithms achieve a constant factor approximation bounds of $0.5(1 - e^{-1})$ and $0.5(1 - e^{-1})$, respectively.*

Proof. Due to space constraints, the reader is referred to the full technical report for detail proofs of above results [33]. \square

6. SIMULATION RESULTS

In this section, we provide a comprehensive evaluation of the proposed optimized framework for video streaming in single-hop networks. In particular, the simulations provide the visual quality of video streams, as measured by mean square error (MSE), when admission control is employed in conjunction with different layer allocation algorithms and the proposed MAC protocol. The layer allocation algorithms of interest are the optimal, the equal rate, the greedy, and the double greedy algorithms. We intentionally omit the results for the triple-greedy algorithm since in our simulations, they are observed to be identical to those of the double-greedy algorithm. This suggests that perhaps for the bit rates and distortion levels of typical video layers, the double-greedy algorithm is sufficient to obtain a good solution.

We note that the optimal algorithm employs an exhaustive search scheme. That is, it examines all the possible combinations of video layers and chooses the one that results in the lowest distortion, that is, smallest MSE that satisfies the bandwidth and distortion constraints. Thus, the optimal algorithm is prohibitively expensive when the numbers of video layers and hosts are large. The optimal algorithm, however, produces the smallest MSE and is thus used to evaluate the goodness of other algorithms. The equal rate algorithm allocates an equal amount of bandwidth to every video (hosts), layer by layer in a round robin fashion until the constraint on total used bandwidth is no longer satisfied. The greedy and double greedy algorithms are previously described in Sections 5.1 and 5.2, respectively.

In all our simulations, we use two sets of standard video profiles, each set consists of three-layered videos, as shown in Tables 1 and 2 [7, 34–37]. Depending on the scenarios, a simulation may use either one or both sets of the video profiles.

6.1. Protocol evaluation

We first compare the performance of the proposed MAC protocol against the standard IEEE 802.11 without admission control [2] and the IEEE 802.11e with admission control. In particular, for the IEEE 802.11e with admission control,

TABLE 1: Standard video profiles—set I.

| Layer | Akiyo | | | Coastguard | | | Foreman | | |
|-------|------------------|------------------|-------------------------------|------------------|------------------|-------------------------------|------------------|------------------|-------------------------------|
| | Bit rates (Kbps) | Distortion (MSE) | Reduction in distortion (MSE) | Bit rates (Kbps) | Distortion (MSE) | Reduction in distortion (MSE) | Bit rates (Kbps) | Distortion (MSE) | Reduction in distortion (MSE) |
| 1 | 64 | — | — | 32 | 123.90 | — | 64 | — | — |
| 2 | 128 | 83.77 | — | 112 | 103.06 | 20.84 | 128 | 71.30 | — |
| 3 | 192 | 63.54 | 20.23 | 160 | 87.72 | 15.34 | 192 | 56.63 | 14.67 |
| 4 | 256 | 50.48 | 13.06 | 208 | 78.18 | 9.54 | 256 | 46.03 | 10.60 |
| 5 | 320 | 38.29 | 12.19 | 256 | 71.30 | 6.88 | 320 | 39.18 | 6.85 |
| 6 | 384 | 32.59 | 5.70 | 304 | 65.03 | 6.27 | 384 | 33.35 | 5.83 |
| 7 | 448 | 27.74 | 4.85 | 352 | 57.95 | 7.08 | 448 | 29.05 | 4.30 |
| 8 | 512 | 23.61 | 4.13 | 400 | 51.65 | 6.30 | 512 | 25.89 | 3.16 |

TABLE 2: Standard video profiles—set II.

| Layer | Foreman 1 (FGS-temporal scalability mode) | | | Coastguard (FGS) | | | Foreman 2 (FGS-AFP mode) | | |
|-------|---|------------------|-------------------------------|------------------|------------------|-------------------------------|--------------------------|------------------|-------------------------------|
| | Bit rates (Kbps) | Distortion (MSE) | Reduction in distortion (MSE) | Bit rates (Kbps) | Distortion (MSE) | Reduction in distortion (MSE) | Bit rates (Kbps) | Distortion (MSE) | Reduction in distortion (MSE) |
| 1 | 140 | 57.03 | — | 110 | 60.68 | — | 384 | 42.96 | — |
| 2 | 240 | 33.05 | 23.98 | 160 | 51.65 | 9.03 | 512 | 31.12 | 11.84 |
| 3 | 340 | 21.89 | 11.16 | 240 | 43.96 | 7.69 | 640 | 26.43 | 4.69 |
| 4 | 440 | 16.30 | 5.59 | 300 | 38.29 | 5.67 | 768 | 22.55 | 3.88 |
| 5 | 540 | 11.46 | 4.84 | 360 | 31.12 | 7.17 | 896 | 19.19 | 3.36 |
| 6 | 640 | 8.67 | 2.79 | 420 | 26.48 | 4.63 | 1024 | 17.91 | 1.28 |
| 7 | 740 | 7.24 | 1.43 | 490 | 24.16 | 2.33 | 1152 | 15.96 | 1.95 |
| 8 | 840 | 5.87 | 1.37 | 590 | 20.56 | 3.60 | 1280 | 14.22 | 1.74 |
| 9 | 940 | 4.59 | 1.28 | 730 | 17.50 | 3.06 | 1408 | 13.27 | 0.95 |
| 10 | | | | 850 | 14.89 | 2.61 | | | |
| 11 | | | | 900 | 11.56 | 3.33 | | | |

we use the mechanism proposed by Banchs et al. [4]. This mechanism is somewhat similar to ours, in the sense that each flow i achieves its throughput by setting the contention window CW_i to an appropriate size. For our proposed MAC, we can approximate $CW_i = 2/p_i$. The fundamental difference, however, is in the formulation which leads to two different algorithms, and consequently different behaviors. In the IEEE 802.11e with admission control, Banchs et al. formulated the admission control process as maximizing the total throughput from all the flows subject to the constraint on the relative throughput for each flow. In particular, the algorithm tries to set the values of the contention window for each flow in such a way to maximize $R = R_1 + R_2 + \dots + R_N$, while ensuring that $R_1/R_1 = n_1$, $R_2/R_1 = n_2, \dots, R_N/R_1 = n_N$, where N , R_i , and $\{n_1, \dots, n_N\}$ are the number of flows, the throughput rate for flow i , and a set of given requirements, respectively. Note that we randomly choose R_1 as a reference flow. As a direct result, the throughput obtained by each flow might be higher than what is specified, especially when the specified aggregate throughput is much smaller than the network capacity. On the other hand, our algorithm produces precisely the specified rate for each flow.

As will explained shortly, the ability to precisely control the rate will enable an efficient cross-layer optimization.

Our simulator is a time-driven, packet-based simulator written in MATLAB. It is designed to mimic as close as possible to the real operations using all the critical parameters in the IEEE 802.11e protocol. For all the simulations, the parameters specified for frequency hopping spread spectrum (FHSS) PHY layer with the channel capacity of 1 Mbps are shown in Table 3. We note that the MAC_{hdr} for IEEE 802.11e contains 2 bytes for a QoS field in addition to that of IEEE 802.11. We also assume that the processing and propagation delays are zero.

We first show the simulation results for a single-hop wireless network consisting of 3 hosts. Each host sends exactly one video to other host over a limited channel capacity (BW) of 1 Mbps. These flows are assumed to be in the same traffic class. The minimum throughput requirements for flows 1 (R_1) and 2 (R_2) are set to 200 Kbps and 300 Kbps, respectively. The minimum throughput of flow 3 (R_3) increases linearly from 115 Kbps to 370 Kbps with a step size of 15 Kbps. For the IEEE 802.11e with admission control, CW_i 's are set according to the admission control

TABLE 3: FHSS system parameters for IEEE 802.11e used to obtain numerical results.

| Parameter | Value |
|----------------------------------|---|
| Packet payload | 1500 bytes |
| MAC header (MAC _{hdr}) | 36 bytes |
| PHY header (PHY _{hdr}) | 16 bytes |
| RTS | 20 bytes + PHY _{hdr} |
| CTS | 14 bytes + PHY _{hdr} |
| ACK | 14 bytes + PHY _{hdr} |
| Channel capacity (BW) | 1 Mbps |
| Slot time | 50 microseconds |
| SIFS | 28 microseconds |
| DIFS | 128 microseconds |
| RTS time out | (RTS/BW × 8 × 10 ⁶) + DIFS microseconds |

algorithm while for the standard IEEE 802.11 without admission control, CW_{\min} and CW_{\max} are set to 15 and 1023, respectively.

Figures 2(a)–2(c) show the observed throughputs for IEEE 802.11 without admission control, IEEE 802.11e with admission control, and our proposed admission control as a function of the flow 3’s throughput. As seen, the standard IEEE 802.11 performs well when the total requested throughput is smaller than the network capacity. Without admission control, however, flow 3 cannot achieve its requested throughput of greater than 320 Kbps. On the other hand, the IEEE 802.11e with admission control performs very well as the throughput for each flow is consistently above its specified minimum requirement. Unlike the IEEE 802.11e, our proposed admission control produces a precise requested throughput for each flow. As a result, the collision rate (wasted bandwidth) is much smaller than that of the standard and the IEEE 802.11e as shown in Figure 2(d), even when the total useful throughputs in both schemes are approximately the same. This is an advantage of using the proposed MAC protocol. Not surprisingly, the total bandwidth usage for our algorithm is much smaller than those of other protocols as shown in Figure 2(e) for a specified set of rates.

We now show the performance of the proposed contention-based MAC protocols when a large number of hosts competing for a shared medium. Specifically, we simulate a scenario consisting of 30 hosts, and the bandwidth capacity is set to 54 Mbps. Each host injects one flow. The throughput of flow 1 (R_1) increases linearly from 120 Kbps to 460 Kbps with a step size of 20 Kbps. The throughput of flow 2 (R_2) increases linearly from 80 Kbps to 590 Kbps with a step size of 30 Kbps. For the remaining flows (R_3 – R_{30}), their throughput requirements are set to 200 Kbps. The parameters specified for direct sequence spread spectrum-orthogonal frequency division multiplexing (DSSS-OFDM) PHY layer with long preamble PPDU format are shown in Table 4. In this simulation, the PHY_{hdr} and the control packets (RTS/CTS/ACK) are sent at only 1 Mbps while the data portion is sent at the full rate of 54 Mbps.

TABLE 4: DSSS-OFDM system parameters for IEEE 802.11e used to obtain numerical results.

| Parameter | Value |
|----------------------------------|-------------------------------|
| Packet payload | 1500 bytes |
| Coding rate | 3/4 |
| MAC header (MAC _{hdr}) | 36 bytes |
| PHY header (PHY _{hdr}) | 32 bytes |
| RTS | 20 bytes + PHY _{hdr} |
| CTS | 14 bytes + PHY _{hdr} |
| ACK | 14 bytes + PHY _{hdr} |
| Channel capacity (BW) | 54 Mbps |
| Slot time | 20 microseconds |
| SIFS | 10 microseconds |
| DIFS | 50 microseconds |
| RTS time out | 352 microseconds |

Figures 3(a)–3(d) show the observed throughputs for IEEE 802.11e resulted from using our proposed admission control as a function of the flow 1’s throughput. As seen, they all achieve the desired throughputs. Note however, because PHY_{hdr} portions and control packets are sent at much slower rate (1 Mbps), this results in low rate of overall data portions as shown in Figure 3(e). Also, the collision rate in our proposed protocol is about 1% of channel capacity when the total bandwidth usage is 90%. Figure 3(f) represents the transmission probability for each host corresponding to their requested throughputs. As seen, our proposed MAC protocol performs reasonably well even in the network with a large number of competing hosts.

We now show the simulation results when applying cross-layer optimization for transmitting 3 video flows. First, to provide some intuitions about the interactions between the proposed MAC protocol and the layer allocation algorithms described in Section 5.2. Specifically, we present the simulation results for various quantities, for example, throughputs, transmission probabilities, when using a simple greedy layer allocation. The simulation parameters are shown in Table 3. Since all video streams are in the same traffic class, they use the same TXOP where TXOP = CTS + PHY_{hdr} + MAC_{hdr} + PAYLOAD + ACK + 3SIFS + DIFS. We use standard video profile set I in this simulation. Figure 4(a) shows the average throughputs of different video streams increasing with the normalized bandwidth usage. From left to right, each point in the graph represents an additional layer being added to one of the videos according to the greedy algorithm. The rightmost point denotes the final number of layers for each video. Adding a layer to any video on each graph at this point would violate the bandwidth constraint. In other words, with the addition of a new layer, Algorithm 2 in Section 3 will not be able to find a set of transmission probabilities that satisfies the requested rates for all the videos. We note that, at this point, the total bandwidth usage is 95%, indicating a relatively high-bandwidth utilization.

Figure 4(b) shows the transmission probabilities for each host as a function of normalized bandwidth usage. As expected, as the number of layers increases for each video,

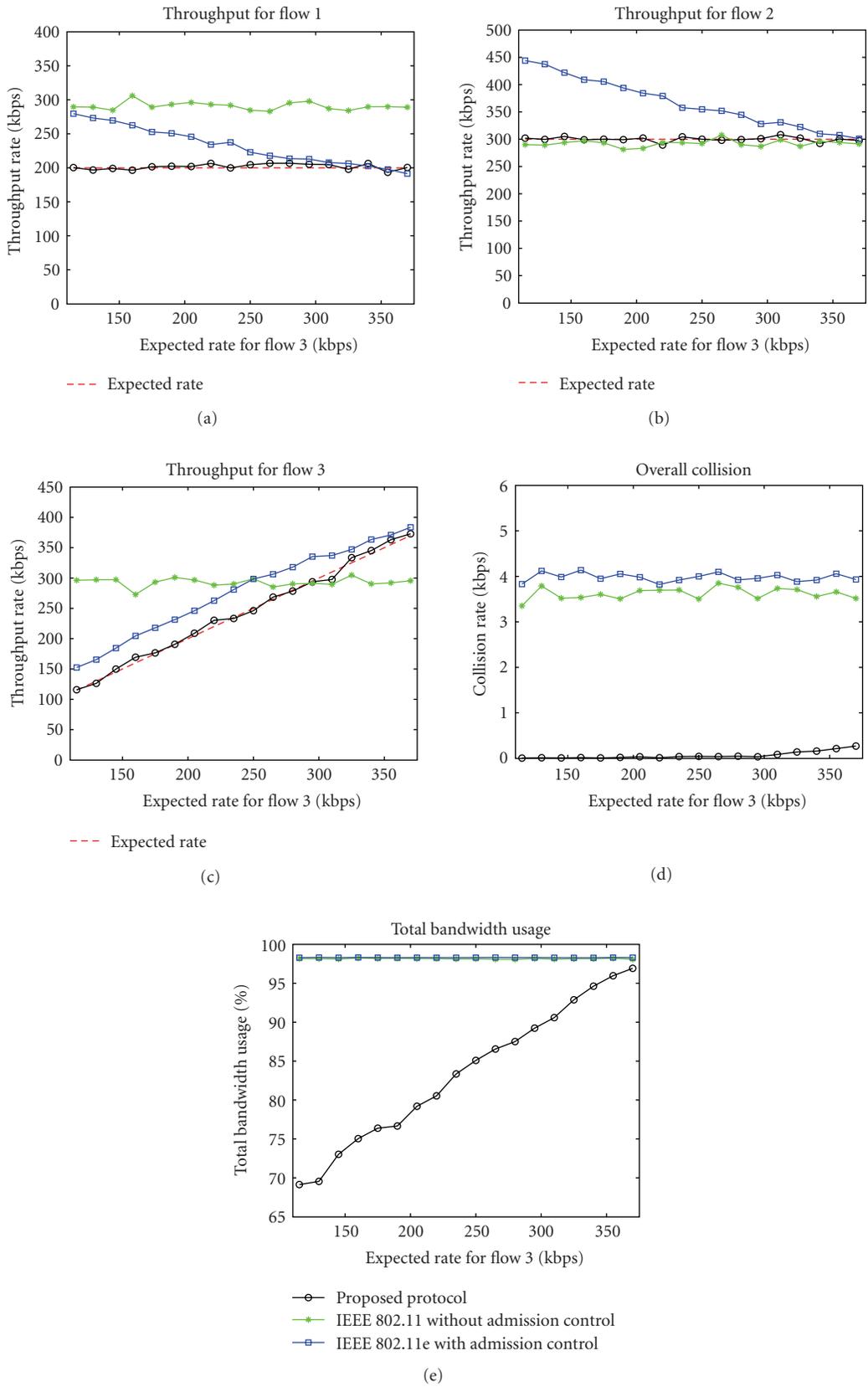


FIGURE 2: Performance comparisons for the proposed protocol versus IEEE 802.11 and IEEE 802.11e protocols. (a) Throughput for flow 1, (b) throughput for flow 2, (c) throughput for flow 3, (d) overall collision, and (e) overall bandwidth usage.

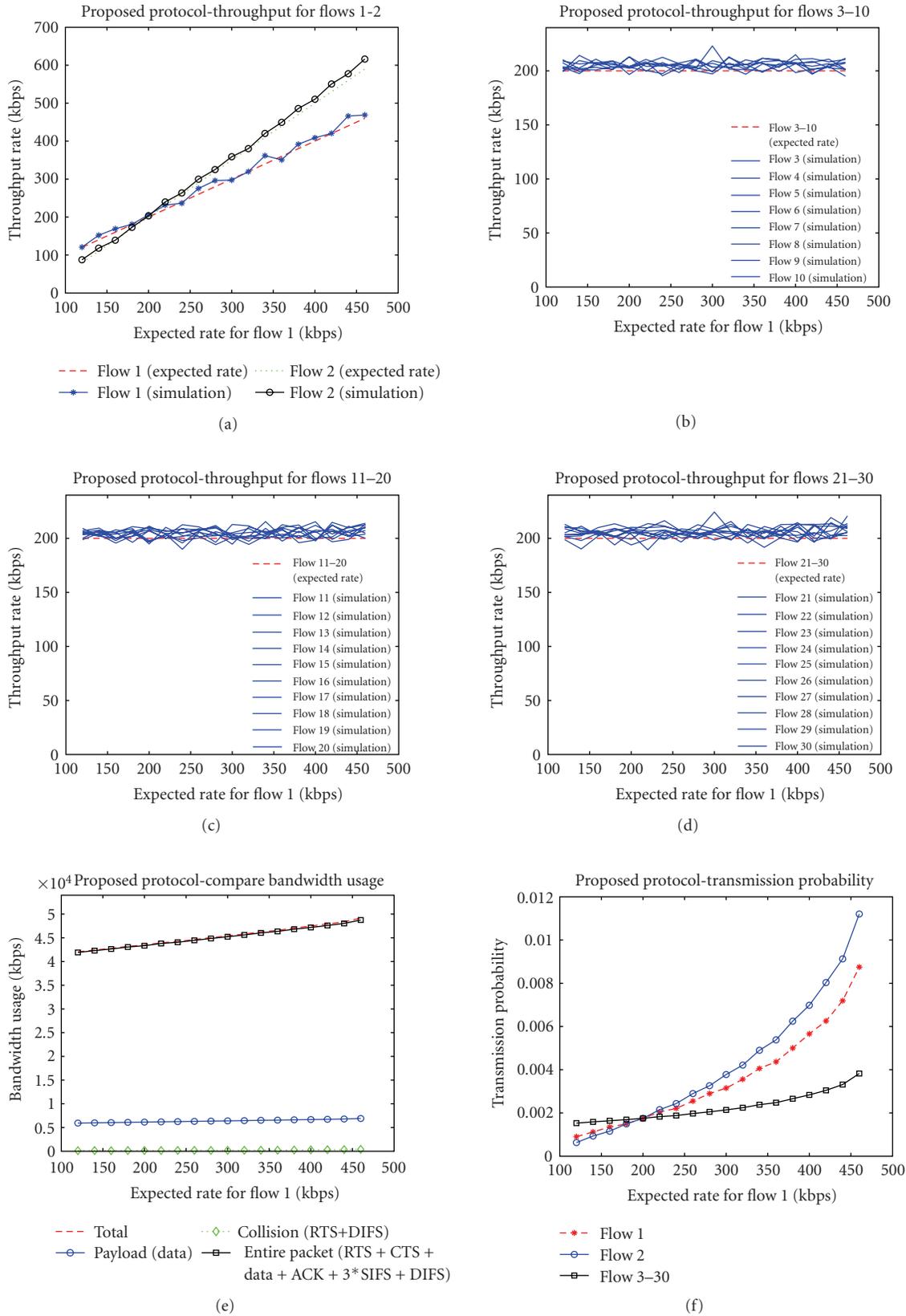


FIGURE 3: Proposed protocol validation with 30 flows over 54 Mbps bandwidth. (a) Throughput for flows 1 and 2, (b) throughput for flows 3-10, (c) throughput for flows 11-20, (d) throughput for flows 21-30, (e) overall bandwidth usage, (f) transmission probability.

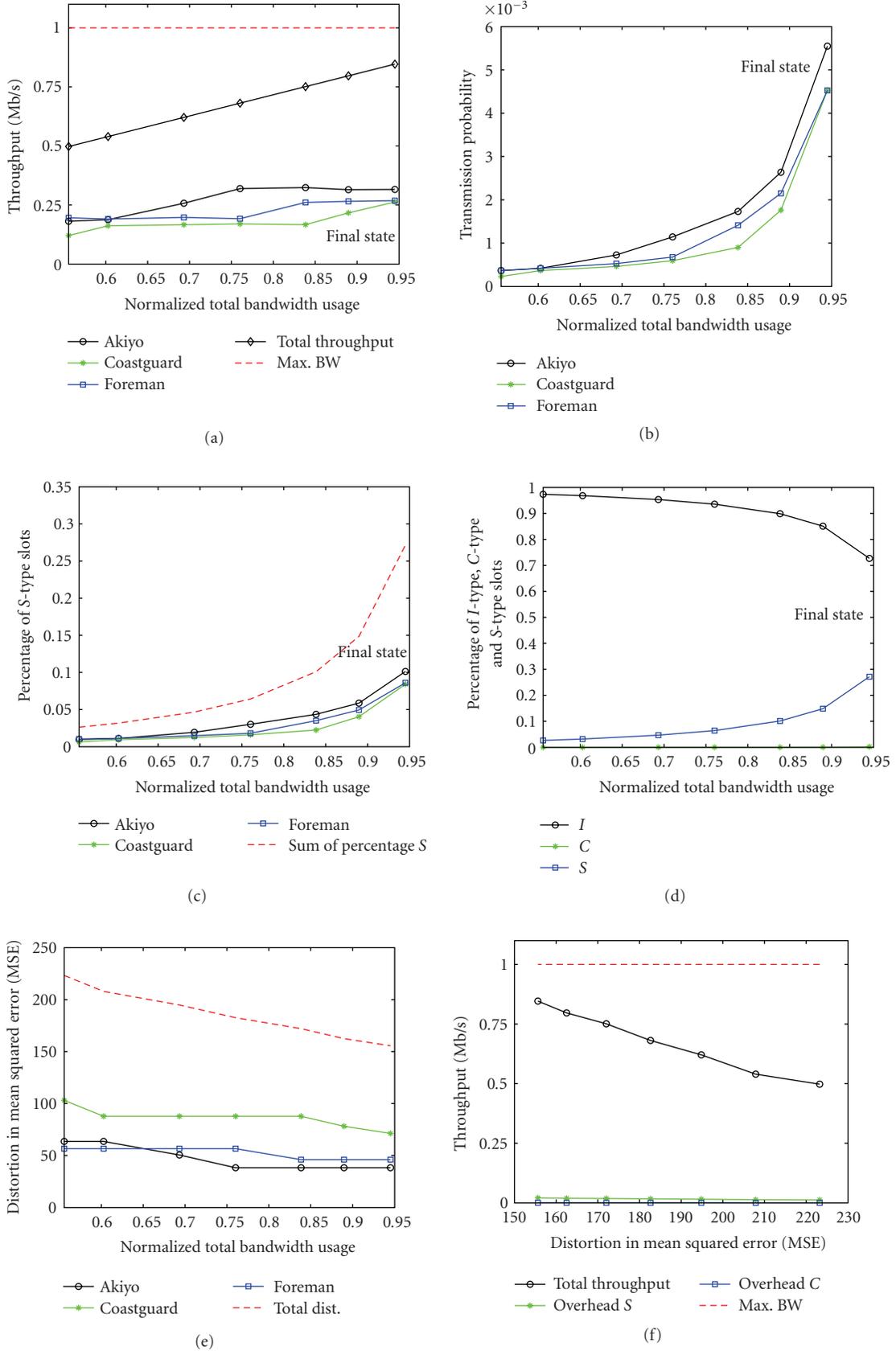


FIGURE 4: Performance results using the greedy algorithm. (a) Throughput, (b) transmission probability; (c) percentage of S slots, (d) percentage of I, C, and S slots, (e) distortion in MSE, (f) rate-distortion characteristic.

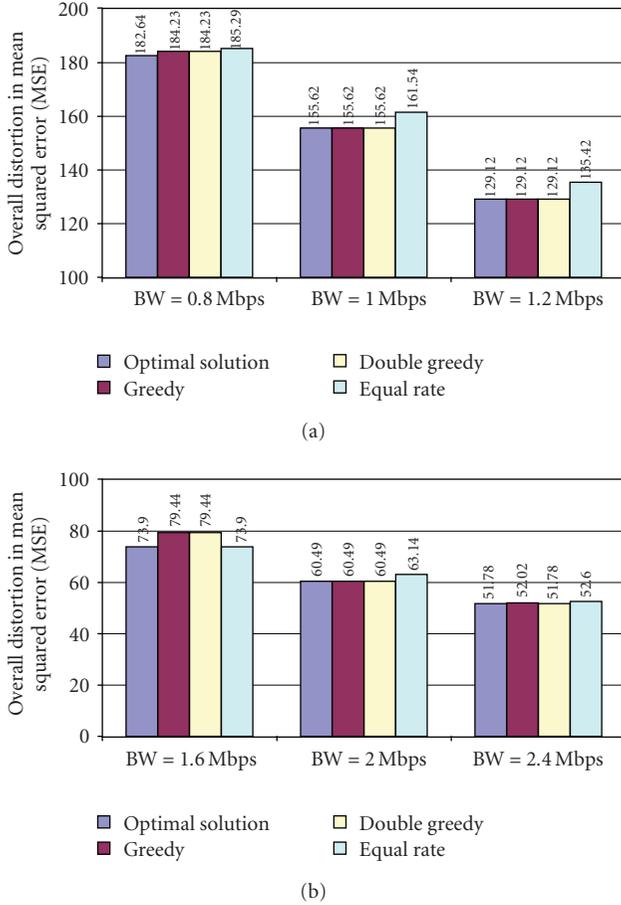


FIGURE 5: Distortion performances of different algorithms for (a) video profiles in Table 1, (b) video profiles in Table 2.

their transmission probabilities also increase accordingly to ensure a higher chance for data transmissions. It is interesting to note that the transmission probabilities increase almost exponentially to compensate for roughly linear increase in the overall throughput. Figure 4(c) shows the corresponding increases percentage of successful slots (over the number of nondata slots) for different video streams, as a direct result of an increase in transmission probabilities.

However, as the transmission probabilities increase, the percentage of collision slots also increases substantially as shown in Figure 4(d). Of course, the percentage of idle slots decreases accordingly. This agrees with our intuition about the proposed MAC protocol. We note that by using this MAC protocol, one is able to control the rate of the flows precisely by tuning their transmission probabilities. These rates, in turn, control the visual quality of the video streams. Figure 4(e) shows the visual quality of the three video streams in terms of MSE as a function of normalized bandwidth usage. In this case, the greedy algorithm, which minimizes the total MSE for all the flows given the bandwidth constraint, yields an MSE of 38, 71, and 46 for Akiyo, Coastguard, and Foreman sequences, respectively. Figure 4(f) shows the actual bandwidth percentage for various packet types. As seen, only minimal bandwidth

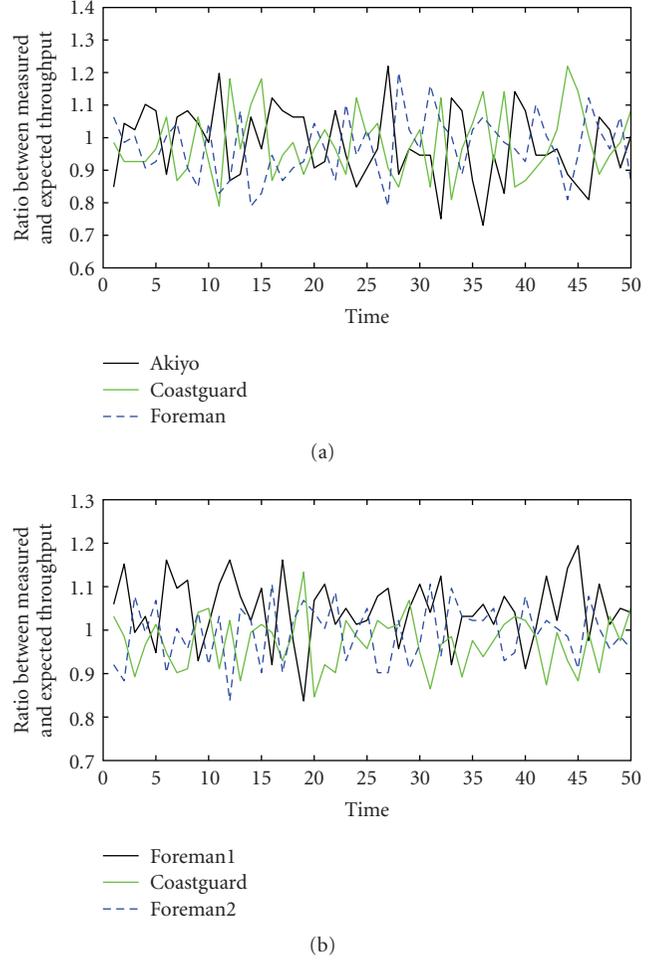


FIGURE 6: Throughput jitter for each flow for (a) video profiles in Table 1, (b) video profiles in Table 2.

overhead (2%) is incurred when using the RTS of 36 bytes and packet payload of 1500 bytes.

6.2. Layer allocation algorithm performance

We now show the performance of different layer allocation algorithms. For simplicity, we assume there is no packet loss. Furthermore, by using standard video profiles H.264/SVC in Table 1, we require that the distortion levels (MSE) for Akiyo, Coastguard, and Foreman cannot be greater than 63, 103, and 56, respectively. For this simulation, these MSE values are chosen rather arbitrarily, but in practice a user can specify his or her visual quality requirement. Figures 5(a) and 5(b) show the distortions resulted from using different algorithms for video profiles in Tables 1 and 2, respectively. For Table 2, the maximum distortion requirements for Foreman 1, Coastguard, and Foreman 2 are 21, 51, and 31, respectively. As expected, the optimal algorithm (exhaustive search) always produces the lowest distortion, albeit it has the highest computational cost.

Figure 5(a) shows that the performances of the greedy and the double greedy are all identical for video profiles

TABLE 5: Detail information associated with different algorithms for video profiles I (BW = 1.2 Mb/s).

| | Distortion | | Normalized bandwidth usage (%) | | | | Transmission probability | | |
|------------------|------------|-------|--------------------------------|------------|------------|--------|--------------------------|------------|---------|
| | (MSE) | Total | Overhead S | Overhead C | Throughput | Others | Akiyo | Coastguard | Foreman |
| Optimal solution | 129.12 | 98.47 | 2.11 | 0.07 | 87.86 | 8.43 | 0.0215 | 0.0269 | 0.0215 |
| Greedy | 129.12 | 98.47 | 2.11 | 0.07 | 87.86 | 8.43 | 0.0215 | 0.0269 | 0.0215 |
| Modified greedy | 129.12 | 98.47 | 2.11 | 0.07 | 87.86 | 8.43 | 0.0215 | 0.0269 | 0.0215 |
| Double greedy | 129.12 | 98.47 | 2.11 | 0.07 | 87.86 | 8.43 | 0.0215 | 0.0269 | 0.0215 |
| Equal rate | 135.42 | 93.56 | 2.00 | 0.02 | 83.52 | 8.02 | 0.0046 | 0.0051 | 0.0046 |

TABLE 6: Detail information associated with different algorithms for video profiles II (BW = 2.4 Mb/s).

| | Distortion | | Normalized bandwidth usage (%) | | | | Transmission probability | | |
|------------------|------------|-------|--------------------------------|------------|------------|--------|--------------------------|------------|-----------|
| | (MSE) | Total | Overhead S | Overhead C | Throughput | Others | Foreman 1 | Coastguard | Foreman 2 |
| Optimal solution | 51.78 | 95.86 | 2.01 | 0.06 | 83.74 | 10.05 | 0.0140 | 0.0129 | 0.0165 |
| Greedy | 52.02 | 97.14 | 2.04 | 0.08 | 84.84 | 10.18 | 0.0203 | 0.0155 | 0.0280 |
| Modified greedy | 51.78 | 95.86 | 2.01 | 0.06 | 83.74 | 10.05 | 0.0140 | 0.0129 | 0.0165 |
| Double greedy | 51.78 | 95.86 | 2.01 | 0.06 | 83.74 | 10.05 | 0.0140 | 0.0129 | 0.0165 |
| Equal rate | 52.60 | 96.47 | 2.02 | 0.07 | 84.26 | 10.12 | 0.0165 | 0.0186 | 0.0165 |

in Table 1. At 0.8 Mbps, the greedy and the double greedy algorithms fail to find the optimal solutions. However, the performances of the greedy, the double greedy, and the optimal algorithms are all identical at the capacity channel of 1 Mbps and 1.2 Mbps. This suggests that greedy and double greedy algorithms perhaps are sufficient in practice. As expected, the equal rate algorithm performs worst since it does not even try to minimize the overall distortion.

On the other hand, Figure 5(b) shows that the greedy algorithm fails to find the optimal solutions in two instances (BW = 1.6 Mbps and 2.4 Mbps). In contrast, the double greedy algorithm typically finds the optimal solutions. This is, however, not guaranteed as the double-greedy algorithm does not converge to optimal solution for BW = 1.6 Mbps. We note that as described in Section 5.2, the computational cost of the double-greedy algorithm is twice that of the greedy algorithm since it must run the greedy and modified greedy algorithms and pick the best one. The modified greedy algorithm is the basic greedy algorithm, where at each step instead of adding the layer that most decreases the distortion, we add the layer that achieves the largest ratio of the reduction in distortion to the layer bit rate, provided that adding the layer does not violate the bandwidth constraint. The modified greedy algorithm might or might not produce a better solution than that of the greedy algorithm. Both the greedy and modified algorithms can produce an arbitrarily bad solution, while the double-greedy algorithm, which returns the best solution (lower distortion) of the greedy and modified greedy algorithms, guarantees that its solution is a constant approximation factor to the optimal solution.

Tables 5 and 6 show the detail information associated with different algorithms for the video profiles I and II, respectively. As seen, the optimal algorithm always achieved in the lowest distortion. In all cases, the bandwidth overhead is relatively small, indicating the ability of the framework to

utilize the bandwidth efficiently. Note that there are some other overhead bandwidths (i.e., PHY_{hdr}, MAC_{hdr}, SIFS, DIFS, ACK) that amount to 8 to 10% of the total bandwidth.

6.3. Throughput jitter evaluation

The proposed optimization framework guarantees that each flow will achieve its required throughput when it is averaged over a long period of time. However, the throughputs of the flows may fluctuate within a short period of time due to the probabilistic nature of the channel contention access. These throughput fluctuations may prevent smooth playback for many audio and video streaming applications. To alleviate this problem, many streaming applications employ the prebuffering technique in which, the receiver puts the received data into a buffer for a short period of time before starting to playback. A longer buffer results in a smoother playback session. On the other hand, using a larger buffer results in larger initial delay and required memory. Interactive applications such as video conferencing may not tolerate such large delay, and the low-power wireless hosts may not have enough memory for buffering. Thus, it is important to characterize the throughput jitter resulting from using the protocol.

Figure 6(a) shows the ratio of the actual throughputs to the requested throughputs of different flows in video profiles I, averaged over every 300 kbytes. The channel capacity is set to 1 Mbps. Figure 6(b) shows throughput ratios for different flows in the video profiles II, averaged over every 600 kbytes, with the capacity channel set to 2 Mbps. As seen, the throughput ratios fluctuate around 1, indicating that all the flows achieve their required throughputs. The magnitudes of these fluctuations are also small (e.g., 0–20%) suggesting that one can use a small streaming buffer for smooth playback.

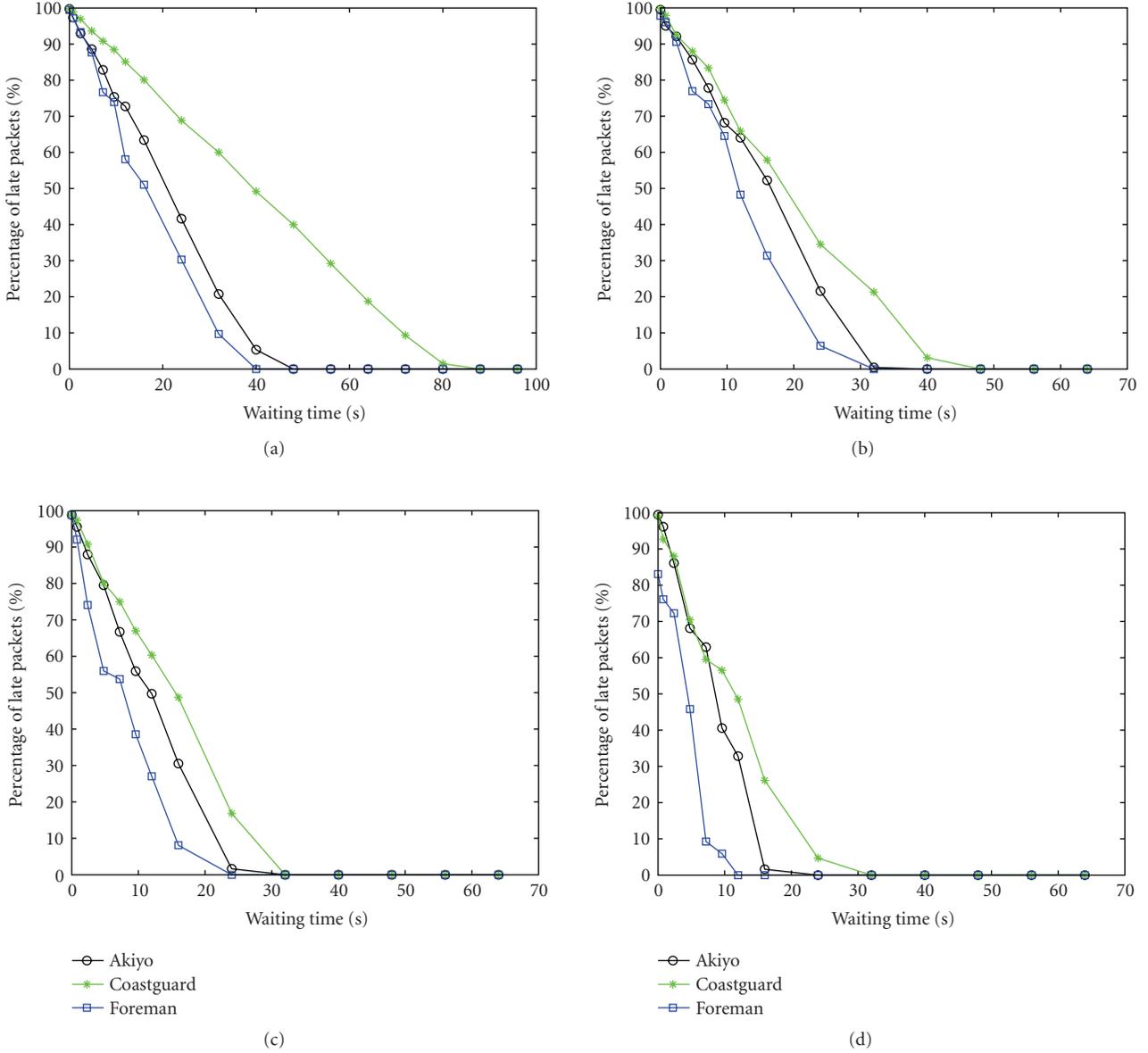


FIGURE 7: Percentage of late packets as a function of streaming buffer length (in seconds); (a) 0% bandwidth safety margin, (b) 1% bandwidth safety margin, (c) 2% bandwidth safety margin, (d) 3% bandwidth safety margin. The bit rates of Akiyo, Coastguard, and Foreman are 192, 160, and 256 Kbps, respectively.

In this simulation, we repeatedly transmit three videos from video profiles I for 20 minutes. We want to quantify how long a streaming buffer should be in order to prevent lost packets due to late arrival. To prevent throughput fluctuation, we also request a slightly larger bandwidth than the recorded video bit rate. This bandwidth safety margin provides robustness against possible throughput depletion during a session. Figure 7(a) to Figure 7(d) show the number of late packets as a function of streaming buffer length for various bandwidth safety margins.

As seen, to have no late packet with no bandwidth safety margin, a user receiving Akiyo needs to wait on average, 48 seconds to smoothly playback a 20-minute video. Users receiving Coastguard and Foreman need to wait up to 88 and

40 seconds, respectively. However, the required waiting time reduces with the increase in the bandwidth safety margin. For example, using the bandwidth safety margin of 3%, the waiting times for Akiyo, Coastguard, and Foreman users are reduced to 24, 32, and 12 seconds, respectively.

We also quantify the throughput jitter of a flow as the normalized standard deviation of its fractional throughput is within a number of time slots. Specifically,

$$\text{Stdev}_n(X_i(T)) = \frac{\text{Stdev}(X_i(T))}{R_i}, \quad (21)$$

where $X_i(T)$ is a fraction of the data slots of the flow i measured within T time slots, and R_i denotes its average

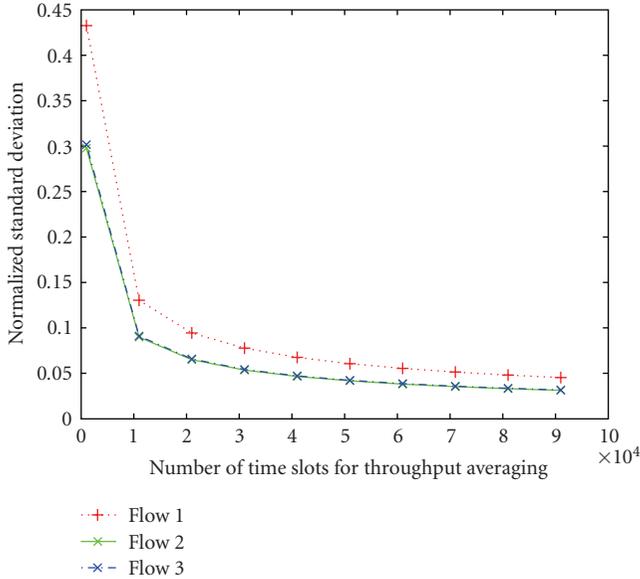


FIGURE 8: Normalized throughput standard deviation as a function of buffer size (T).

long-term fractional throughput. Clearly, a larger T should result in a smaller normalized throughput standard deviation since we average the throughput over a longer period of time. It is straightforward to show that

$$\text{Stdev}_n(X_i(T)) = \text{TXOP}_i \times \frac{\sqrt{(1 - \sum_{i=1}^N R'_i) \times S_i \times (1 - S_i)}}{R'_i \sqrt{T}}, \quad (22)$$

where N denotes the number of flows and S_i 's denotes the number of successful time slots for flow i . (This result can be obtained by noticing that the number of successful transmission slots within a period T is binomially distributed with parameters S_i and $T(1 - \sum_{i=1}^N R'_i)$.)

To quantify the normalized throughput standard deviation, we simulate three flows with R'_1 , R'_2 , and R'_3 being set to 0.1, 0.27, and 0.4, respectively. Figure 8 shows the normalized throughput standard deviations for three different flows as a function of buffer size (T). As expected, as T increases, the normalized throughput standard deviation decreases. However, increasing T implies an increase in playback delay.

6.4. Overall performance

We now compare the performance of our proposed framework against the existing IEEE 802.11 without admission control and IEEE 802.11e with admission control proposed by Banchs et al. [4]. To simulate realistic settings, packet losses are introduced into the simulations. For simplicity, we assume that packet loss rates are identical for all the receivers. We also assume that a packet will be transmitted repeatedly until it is received successfully. As a result, the useful throughput reduces with an increase in packet loss rate. The admission control module is assumed to be able to measure the packet loss rate, and thus can determine

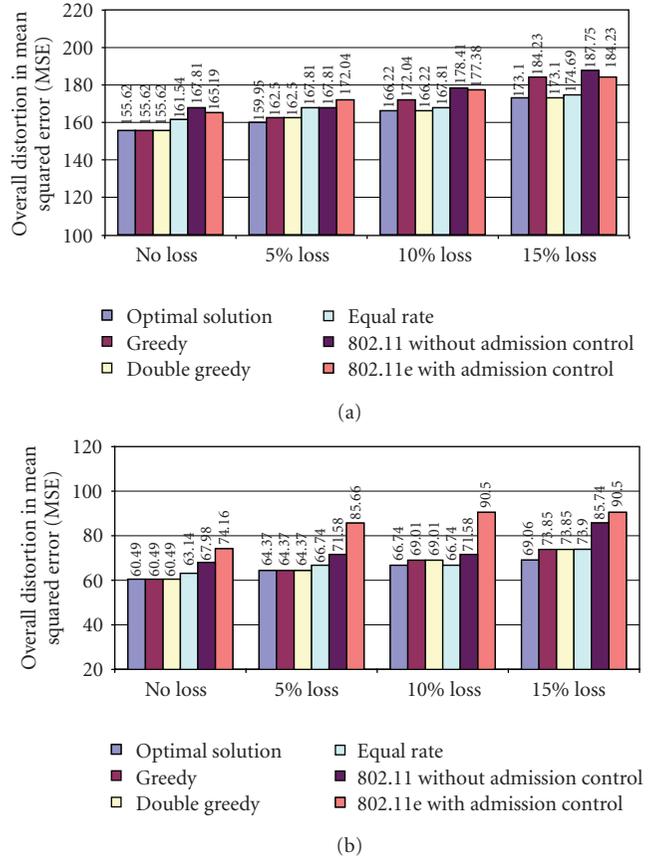


FIGURE 9: Distortions resulted from using various protocols: (a) using video profiles I with channel capacity set to 1 Mbps, (b) using video profiles II with channel capacity set to 2 Mbps.

the overall effective throughput. Using the overall effective throughput and the video profiles as inputs, it can use different optimization strategies to allocate bandwidths for receivers to minimize the average distortion.

Figure 9(a) shows the average distortion for various strategies when streaming the videos in profile I. As expected, the optimal strategy, that is, exhaustive search, always provides the smallest average distortion. The double-greedy algorithm also performs equally well. The greedy algorithm performs slightly worse, followed by the equal rate algorithm, the IEEE 802.11 protocol without admission control, and IEEE 802.11e with admission control. The main reason for the worse performances when using the IEEE 802.11 and the IEEE 802.11e is the lack of layer allocation optimization. For the IEEE 802.11, due to the random contention-based access where each flow has an equal chance of accessing the shared channel, all three flows obtain approximately the same throughputs. However, this is not the optimal allocation for minimizing the overall distortion. Intuitively, the IEEE 802.11 should perform as well as the equal rate allocation. On the other hand, the equal rate allocation scheme uses the proposed admission control which results in smaller collision bandwidth as compared to that of IEEE 802.11. As a result, the average distortion of the equal rate scheme is typically lower than that of the IEEE 802.11.

However, admission control mechanism alone does not improve the quality of the video. To see this, let us consider the performance of the IEEE 802.11e with admission control. Using this scheme, one is able to guarantee the minimum throughput rate for each flow. However, if after providing these minimum throughputs for the flows, there is still much bandwidth available, then as designed, the IEEE 802.11e protocol would allow each flow to increase its throughput proportionally until the wireless capacity is reached. The final throughput of each flow as obtained by the admission control algorithm then dictates the quality of a video. In other words, the layer allocation employed in this case is to allocate the rate proportionally according to the initial conditions. For example, if the minimum rates (or equivalently maximum distortions) for three flows are specified initially 200 Kbps, 400 Kbps, and 400 Kbps, then with a channel capacity of 2 Mbps, the IEEE 802.11e protocol will roughly allocate 400 Kbps, 800 Kbps, and 800 Kbps for these flows (for sake of illustration, we assume no collision bandwidth). Clearly, this allocation is not optimal as it does not take into account the distortion profile for each video. That said, there is no reason why the IEEE 802.11e with admission control should perform better than the IEEE 802.11 or other schemes when there is enough bandwidth. In fact, Figure 9(b) shows that the IEEE 802.11e results in a larger average distortion consistently when using video profiles II. Our proposed framework which integrates the admission control with layer allocation optimization enables us to achieve the lowest distortion. Overall, our proposed framework improves the video quality up to 26% over that of a typical IEEE 802.11 based network.

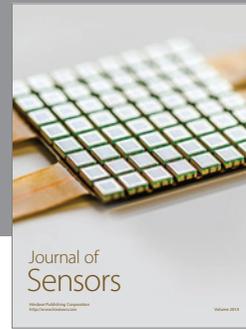
7. CONCLUSIONS

We have proposed a framework to enhance the quality of video streaming applications in wireless home networks via a joint optimization of video layer-allocation technique, admission control algorithm, and MAC protocol. Using an Aloha-like MAC protocol, our admission control framework which can be viewed as an optimization problem that maximizes the average quality of admitted videos, given a specified minimum video quality for each flow. We provided some hardness results for the optimization problem under various conditions and proposed two heuristic algorithms for obtaining a good solution. In particular, we showed that a simple greedy layer-allocation algorithm can perform reasonable well, although it is typically not optimal. Consequently, we presented a more expensive heuristic algorithm that guarantees to approximate the optimal solution within a constant factor. Based on our scenario, simulation results demonstrated that our proposed framework can improve the video quality up to 26% as compared to those of the existing approaches.

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