

Performance Evaluation of IPTV Over Wireless Home Networks

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Abstract—The emergence of Internet Protocol Television (IPTV) has brought potentials to revolutionize personal entertainment. Streaming TV content over the highly pervasive wireless networks allows easy access to personalized entertainment. Focusing on wireless home entertainment which is one of the main driving forces of IPTV development, we develop a Markovian framework that investigates several important issues related to network capacity and streaming quality in an IEEE 802.11e enabled wireless home network. The Markovian framework captures not only the IEEE 802.11e MAC protocol performance, but also the statistical characteristics of IPTV media streams. The inclusion of these two key descriptions allows our model to be practically used in wireless home network planning and design. To deal with the complexity in the model, we apply the efficient Matrix Geometric approach to obtain numerical results. We further perform simulations with real IPTV traffic to not only validate our analytical results, but also obtain further insight to the performance.

Index Terms—IEEE 802.11e wireless home networks, Internet Protocol Television (IPTV), performance evaluation.

I. INTRODUCTION

THE high penetration of wireless home networks has encouraged network applications in the home environment. One of the exciting applications for wireless home networks is Internet Protocol Television (IPTV) which aims to stream TV contents over the Internet. The ability to stream TV contents over wireless Internet not only allows TV contents to reach an even wider range of devices, but also offers great flexibility in time and space control for personal enjoyment.

The current popular wireless home networks use the wireless technologies specified in the IEEE 802.11 standards. The IEEE 802.11 working groups specify a series of wireless communication technologies and medium access control (MAC) protocols that keep the advancement of wireless local area networks (WLANs). Some important standards related to this study include the IEEE 802.11b standard specifying the operation of up to 11 Mbps data rate on the 2.4-GHz wireless channel

[1], the IEEE 802.11g standard enhancing the operation to 54 Mbps data rate on the 2.4-GHz wireless channel [2], the IEEE 802.11e standard specifying the enhanced distributed channel access (EDCA) to provide quality-of-service (QoS) support to the IEEE 802.11 WLANs [3], and the recently standardized IEEE 802.11n standard enhancing the operation to 100 Mbps data rate [4]. With these constant efforts of enhancements, the IEEE 802.11 WLANs have prepared themselves not only to provide wireless Internet access for best effort (BE) traffic, but also to deal with future network applications with high demand in bandwidth and QoS such as multimedia-rich applications [5], [6].

As we witness the advancements in WLANs in the last decade, we also see increasing demand of high-quality media from the traditional low-resolution media to the current DVD quality media, the emerging HDTV quality media, and the potential new arrival of 3-D TV media. IPTV, in which video content is digitized and sent to individual receivers as IP packets, is adopted for most recent media development. IPTV media can be accessed on multipurpose devices instead of traditional TV devices with some dedicated functions. The content of IPTV can be personalized and accessed from locations where Internet connectivity is available. Although a widely-acceptable IPTV standard is not available yet [7], the current popular coding schemes for IPTV include H.264 advanced video coding (AVC), H.264 medium grained scalability coding (MGS), and H.264 scalable video coding (SVC). The rapid evolution of IPTV media in recent years has prompted the urgency in the investigation of the WLAN support. The investigation of the WLAN support for IPTV media is especially important for the IEEE 802.11 WLAN due to its employment of contention-based operation for both channel access and QoS support. The mechanism of the contention-based operation in IEEE 802.11 WLAN gives rise to uncertainties in the efficiency of channel access and effectiveness of QoS support.

As demonstrated in our previous work in [8] focusing on the IEEE 802.11 MAC protocol performance analysis, significant differences in performance exist between a more precise and a less detailed model for the description of the protocol service behavior and the source arrival models. As discussed in [8], the service time distribution of the IEEE 802.11 MAC protocol can be modeled appropriately by Erlang distribution. This permits the construction of a Markovian framework to study the performance of the IEEE 802.11 WLAN under traffic arrivals which can be described by a Markovian arrival process (MAP) [8], [9]. Specifically, it motivates us to design an accurate model for evaluating IPTV performance over WLANs. The contributions of this paper are twofold.

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- Firstly, we present a Markovian framework that investigates the performance of IPTV streaming over the QoS-enabled IEEE 802.11e WLANs. Different from our earlier work [8] which focuses on the proposal of a Markovian framework to describe the service behavior of IEEE 802.11 MAC protocol, this paper considers the IEEE 802.11e network (with QoS feature) as well as the IPTV traffic, where we develop an equivalent MAP to describe the IPTV traffic arrivals and an appropriate phase-type service time distribution to model the EDCA service behavior. To the best of our knowledge, this is the first Markovian framework that can capture the detailed behaviors of IPTV and the IEEE 802.11e EDCA.
- Secondly, to deal with the complexity added by capturing detailed behaviors of IPTV and the IEEE 802.11e EDCA in a Markovian framework which produces more representative performance to the studied scenario, we use the efficient Matrix Geometric approach for the numerical computation.

With the developed Markovian framework, we study the channel capacities (in terms of the number of simultaneous IPTV streams) of various popular IEEE 802.11 versions with the IEEE 802.11e QoS support. We perform simulation experiments to validate our modeling approach and study the performance with aggregated realistic inputs using real video traffic.

The rest of the paper is organized as follows. In Section II, we discuss the related work on the performance evaluation of IPTV over wireless home networks. In Section III, we introduce a typical scenario of IPTV over wireless home networks. In Section IV, we present our developed Markovian framework, describing the modeling of IPTV traffic arrivals and IEEE 802.11e service behavior. In Section V, we show the numerical and simulation results emphasizing the system capacity and the performance characteristics especially under heavy load conditions. Finally, important conclusions are drawn in Section VI.

II. RELATED WORK

The importance of developing understanding of the performance of IPTV over the wireless Internet has been highlighted in several recent works (see [10]–[14] and the references therein). Yang *et al.* [10] claimed that IPTV, as the killer application for the next-generation Internet, needs further investigation and research on detailed performance evaluations in WLANs. Such performance studies can largely be conducted by either empirical experimentation, simulation experimentation, or system modeling.

In [11], Djama and Ahmed evaluated the packet losses and the perceived quality of the TV service using an experimental test-bed. The results obtained from the test-bed well validate the algorithms proposed in [11]. However, the test-bed based performance evaluation suffers from time-consuming realization and complex setup.

Du and Zhang [12] proposed an efficient model to study the statistical QoS guarantees, in terms of effective bandwidth/capacity and delay-bound violation probability, for multi-layer video transmission over wireless fading channels. However, the multi-layer video arrival process was only managed by separate

queues, which did not take the statistical characteristics of video traffic into consideration.

Shihab *et al.* [13], [14] investigated the performance of IPTV packet loss caused by buffer overflow in several home network scenarios including wired link with a constant data rate, single hop wireless link with a variable data rate, and a multi-hop wireless path. For the arrival process, an on-off traffic source was used to describe the video source. For the service process, an exponential distribution was assumed for the service time distribution of the considered data links. The use of an on-off arrival model for video sources and an exponential service time distribution for complex network protocol behaviors such as the IEEE 802.15.3 or the IEEE 802.11 MAC protocols greatly limits the practicability of the analytical results. Li and Pan [15] proposed an extended two-dimensional Markov-chain model to analyze the throughput of IEEE 802.11 multi-hop wireless networks, where the error-prone channel, non-persistent traffic, post-backoff stage, and finite retry limit were taken into account. The throughput analysis provides the upper-bound throughput performance of video streaming. However, the considered traffic is a general non-persistent traffic which lacks description on video characteristics.

III. SCENARIO

The tremendous growing of the IEEE 802.11 WLANs deployed in the home environment in recent years has encouraged the use of IP networks for various traditional and new network applications, such as networking of home appliances, home security, and also IPTV. There are, however, challenges in using a single common wireless home network for home network applications with increasing demands in bandwidth and QoS requirements. The shared wireless channel architecture in WLANs introduces a bottleneck in the network and the employment of contention-based MAC protocol poses uncertainty in the efficiency of the WLANs. These problems have amplifying effect especially in multimedia applications such as IPTV as they demand high and steady bandwidth to provide adequate operations. Anticipating the increasing demand for personal entertainment in the home environment, IPTV will be the next key application in wireless home networks. To develop a theoretical understanding, this paper studies the performance of IPTV streaming over wireless home networks.

Fig. 1 illustrates our considered scenario of IPTV streaming over wireless home networks. Factoring the potential application of personal entertainment in wireless home networks, we consider a scenario of simultaneous IPTV streams in the wireless home network environment, where different IPTV traffic packets are transmitted by unicast to different users. We believe that the IPTV service that offers personalized entertainment is likely to rely on unicast transmission heavily, which is different from the traditional broadcast of TV contents. On the other hand, in terms of system capacity, the analytical model developed in this paper for unicast can also be used to provide estimation for the case of multicast transmission, where the video stream being multicast can be seen as one unicast video stream.

Additionally, the considered wireless home network also carries some amount of BE traffic generated by other network applications. All IPTV users are equipped with a wireless set-top

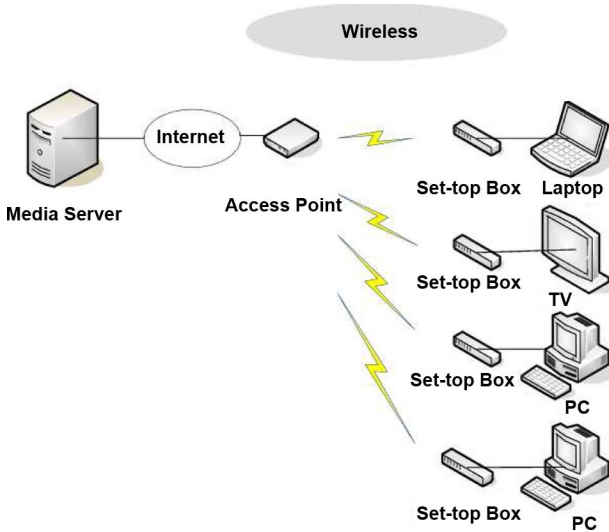


Fig. 1. Scenario example of IPTV over wireless home networks.

box to communicate with a media server on the Internet via the access point (AP) over the wireless home network. In this setup, the AP acts as a relay that forwards the received IPTV streams to all IPTV users over a wireless link.

Given the robust first mile access network and high-speed connectivity between the Internet and a wireless home network, it is expected that streaming of IPTV will find transmission bottleneck at the wireless link within the wireless home network. We assume that the AP enjoys a 100 BASE-T connectivity to the Internet. Our scenario considers various wireless technologies that offer 11 Mbps, 54 Mbps, and 100 Mbps physical data rates, with the IEEE 802.11e EDCA QoS implementation.

The IPTV transmission process can be described as follows. An IPTV user tunes to a particular program where the set-top box makes a request accordingly to the media server. The media server then starts to stream the IPTV traffic over the Internet and the wireless home network to the IPTV user. The IPTV traffic is packetized using RTP/UDP/IP protocols. The IPTV traffic is typically encoded with a pattern of one I frame followed by many P frames or B frames to form a group of pictures (GoP) [16]. Each frame is encoded and packetized into one video packet in the application layer which may be subjected to fragmentation in the lower layers. At the receiver side, each frame is decoded from received packets. In the event of a packet loss, not only the frame within the lost video packet is lost, but also the subsequent frames that rely on the lost video frame to decode in the same GoP are considered lost. A lost frame is then replaced by the previously decoded frame for error concealment.

IV. MODEL DESCRIPTION

Following our previous modeling approach in [8], we develop a Markovian framework to model the described scenario. Precisely, we use a particular MAP to describe the aggregated IPTV streams and a phase-type distribution to describe the service time distribution of the IEEE 802.11e with a certain data rate. In the following subsections, detailed models for the arrival and service processes are described.

A. Traffic Arrival Model

Our scenario consists of two types of traffic which are IPTV traffic and best effort data traffic. We use two different arrival models to describe these two types of traffic.

For the IPTV traffic arrival model, we consider the statistical characteristics of the IPTV traffic. From the point of view of the AP, the arrival of an IPTV packet is the event that an IPTV packet has arrived at the AP from the Internet ready to be delivered to the intended end user via the wireless link. Given a particular IPTV content, the content is encoded and packetized into a stream of IP packets, each of which is encapsulated into an IEEE 802.11 data frame. Adapting a common traffic shaping control at the video encoding process and ignoring the encoding processing time, it is adequate to describe this IP packet stream using a variable bit rate (VBR) traffic model. One appropriate VBR traffic model is Erlang distribution that specifies the distribution of the inter-arrival time [9].

An Erlang distribution can be characterized by two parameters, namely the number of exponential phases k and the exponential rate λ . These two parameters control the mean and variance of the distribution, where the mean of an Erlang distribution is k/λ and the variance is k/λ^2 . By measuring the mean and variance of the packet inter-arrival time of an IPTV traffic trace, we can calculate the corresponding Erlang distribution parameters, k and λ .

In modeling of an aggregated IPTV traffic stream formed by n different IPTV traffic streams, we again use Erlang distribution for the inter-arrival time distribution. The two parameters, k and λ_v , of the Erlang distribution are now fit based on the aggregated traffic. The arrival rate r_v (in bps) of the IPTV traffic can then be calculated as

$$r_v = \frac{L_v \cdot \lambda_v}{k} \quad (1)$$

where L_v is the average IPTV packet length.

Our model also considers some amount of BE traffic transmission in the network. We use a simple model of Poisson process to describe the BE arrival process. To appropriately model BE traffic transmission in the IEEE 802.11 WLANs, the uplink BE traffic and the downlink BE traffic are modeled separately. We use λ_{pa} and λ_{ps} to describe the arrival rates of the downlink BE traffic sent by the AP, and the aggregated uplink BE traffic sent by all stations, respectively.

B. IEEE 802.11e Service Model

In this subsection, we present a phase-type model that describes the IEEE 802.11e MAC protocol service behavior. We have studied the IEEE 802.11 MAC protocol in our earlier work, where we illustrate the use of Erlang distribution to describe the service time distribution of the IEEE 802.11 MAC protocol [8]. Precisely, our study shows that for the IEEE 802.11 MAC protocol service process, its service time for each packet follows Erlang distribution. Using Bianchi's model [17], we can determine the average service time for a packet given a particular number of active stations in the network.

To deal with the IEEE 802.11e MAC protocol that features the QoS support, a saturation throughput analysis of the IEEE 802.11e MAC protocol is needed. In [18], we extended

TABLE I
 STATE TRANSITION FOR THE BIRTH PROCESS FROM CURRENT STATE $(k_v, i, j, k_{p_s}, k_{p_a})$

Condition	Transition rate (packets/s)	Next state	Description
$[(k_{p_a} = 0) \& (k_{p_s} = 0) \& (k_v = 0) \& (i = I-1) \& (j = 0)]$	λ_v	$(1, 0, J - 1, 0, 0)$	One IPTV packet has completed its arrival process and enters the first service phase when there is no packet in the buffer.
$(k_v < V) \& (i < I-1)$	λ_v	$(k_v, i + 1, j, k_{p_s}, k_{p_a})$	One IPTV packet has transited to the next Erlang phase but yet to complete an arrival process.
$(k_v < V - 1) \& (i = I-1)$	λ_v	$(k_v + 1, 0, j, k_{p_s}, k_{p_a})$	One IPTV packet has completed its arrival process and enters the first service phase.
$k_{p_s} < PS - 1$	λ_{p_s}	$(k_v, i, j, k_{p_s} + 1, k_{p_a})$	A BE packet from a station has arrived.
$k_{p_a} < PA - 1$	λ_{p_a}	$(k_v, i, j, k_{p_s}, k_{p_a} + 1)$	A BE packet from the AP has arrived.

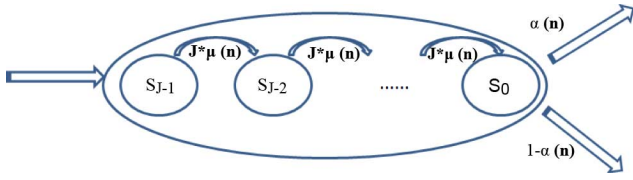


Fig. 2. Phase-type model for the IEEE 802.11e MAC protocol service process.

Bianchi's work [17] and presented a model of the IEEE 802.11e MAC protocol for saturation throughput analysis. The IEEE 802.11e supports four classes of traffic, namely voice, video, best effort, and background traffic. Our model gives a number of performance measures including numerical results for overall network throughput and service ratio among different types of traffic, which are needed to parameterize the phase-type model for the IEEE 802.11e MAC protocol service behavior.

Our proposed phase-type model for the IEEE 802.11e MAC protocol service process is depicted in Fig. 2. In the model, J is the total number of phases, and S_j is the network state when the service phase of one packet is j . $\mu(n)$ denotes the overall service rate of the IEEE 802.11e MAC protocol given n active stations and one AP, and $\alpha(n)$ denotes the probability that a served packet is an IPTV packet. The computation of $\mu(n)$ and $\alpha(n)$ can be found in the Appendix. Note that, as shown in Fig. 2, the transition rate between neighboring phases is $J \cdot \mu(n)$ because a packet goes through J phases to complete the service with a service rate of $\mu(n)$.

C. Markovian Framework

We develop a Markovian single server queue (SSQ) to study IPTV streaming performance over a wireless home network. In this SSQ, the birth process is modeled by the MAP and the death process is modeled by the phase-type distribution. The Markovian SSQ is described into a continuous-time Markov chain (CTMC) of five dimensional states, $(k_v, i, j, k_{p_s}, k_{p_a})$, where

- k_v is the number of video packets in the AP buffer waiting for downlink transmission, $0 \leq k_v < V$. The maximum buffer size in the AP for video packets is $V - 1$;
- i is the current phase of the IPTV video arrival in the Erlang distribution, $0 \leq i < I$, where I is the total number of phases;

- j is the current service phase in Erlang distribution, $0 \leq j < J$, where J is the total number of phases;
- k_{p_s} is the number of stations carrying a BE packet to transmit to the AP, $0 \leq k_{p_s} < PS$. The maximum number of BE stations in the network is $PS - 1$, which is equal to n ;
- k_{p_a} is the number of BE packets in the AP buffer waiting for downlink transmission, $0 \leq k_{p_a} < PA$. The maximum buffer size in the AP for BE packets is $PA - 1$.

Tables I and II describe the one-step state transition of the birth and death transition processes of the designed SSQ, respectively. Each specified condition in the table indicates the validity of the corresponding transition to the next state with the transition rate. There are three possible events in the birth process: an advancement of an Erlang phase of an IPTV packet, an arrival of a BE packet from a station, and an arrival of a BE packet from the AP. The death process in our model corresponds to a departure of a packet or the completion of an Erlang service phase for an IPTV packet if the Erlang service phase is not the last phase. The departing packet may be a BE packet from either a station or the AP, or an IPTV packet that has completed its last Erlang service phase.

Let $x_{k_v, i, j, k_{p_s}, k_{p_a}}$ be the steady-state probability that the system operates in state $(k_v, i, j, k_{p_s}, k_{p_a})$ and \mathbf{x} be the vector holding $x_{k_v, i, j, k_{p_s}, k_{p_a}}$ for all possible states. The mapping of the five-dimensional state space onto a unidimensional space indexed by q is achieved by

$$\begin{aligned}
 q = & i + j \cdot I + k_v(I \times J) + k_{p_a}(I \times J \times V) \\
 & + k_{p_s}(I \times J \times V \times PA) \\
 & - I \times (J - 1) \times \min(1, k_{p_a} + k_{p_s} + k_v) \quad (2)
 \end{aligned}$$

where the last term is to take into account that there are only I states at $k_{p_a} = k_{p_s} = k_v = 0$. Essentially, (2) maps a five-dimension state to a unique non-negative integer number.

With the above setup, the infinitesimal generator of this CTMC can be denoted by a transition matrix Q , describing all the possible transitions from one state to another. With the

TABLE II
STATE TRANSITION FOR THE DEATH PROCESS FROM CURRENT STATE $(k_v, i, j, k_{p_s}, k_{p_a})$

Condition	Transition rate (packets/s)	Next state	Description
$[(k_{p_a} = 0) \& (k_{p_s} = 0) \& (k_v = 1)] \& (j = 0)$	$\mu(n)$	$(0, i, 0, 0, 0)$	One packet has finished its service process and no packet is waiting for service.
$[(k_{p_a} = 0) \& (k_{p_s} = 1) \& (k_v = 0)] \& (j = 0)$	$\mu(n)$	$(0, i, 0, 0, 0)$	
$[(k_{p_a} = 1) \& (k_{p_s} = 0) \& (k_v = 0)] \& (j = 0)$	$\mu(n)$	$(0, i, 0, 0, 0)$	
$[(k_{p_a} \geq 0) \& (k_{p_s} > 0) \& (k_v \geq 0)] \& (j = 0)$	$\mu(n) \cdot (1 - \alpha(n)) \cdot \frac{k_{p_s}}{k}$	$(k_v, i, J - 1, k_{p_s} - 1, k_{p_a})$	One packet has finished its service process.
$[(k_{p_a} > 0) \& (k_{p_s} \geq 0) \& (k_v \geq 0)] \& (j = 0)$	$\mu(n) \cdot (1 - \alpha(n)) \cdot \frac{1}{k}$	$(k_v, i, J - 1, k_{p_s}, k_{p_a} - 1)$	
$[(k_{p_a} \geq 0) \& (k_{p_s} \geq 0) \& (k_v > 0)] \& (j = 0)$	$\mu(n) \cdot \alpha(n)$	$(k_v - 1, i, J - 1, k_{p_s}, k_{p_a})$	One packet has transited to the next Erlang service phase but yet to complete the entire service process.
$[(k_{p_a} > 0) \& (k_{p_s} > 0) \& (k_v > 0)] \& (0 < j < J)$	$\mu(n)$	$(k_v, i, j - 1, k_{p_s}, k_{p_a})$	

$$k = k_{p_s} + \min\{1, k_{p_a}\}$$

Matrix Geometric approach, this transition matrix Q can be organized and partitioned into several sub-matrices as

$$Q = \begin{bmatrix} B & C & & & \\ & E & A_1 & A_0 & \\ & & A_2 & A_1 & A_0 \\ & & & A_2 & A_1 & A_0 \\ & & & & \ddots & \ddots & \ddots \end{bmatrix} \quad (3)$$

where each of the sub-matrices, $A_0, A_1, A_2, B, C,$ and $E,$ is finite, describing the evolution of a specific state. In particular, the sub-matrix B contains the state transitions among states satisfying $k_{p_s} = 0,$ and the sub-matrix E contains the state transitions from any state satisfying $k_{p_s} = 1$ to a state satisfying $k_{p_s} = 0.$ Likewise, the sub-matrix C contains the state transitions from any state satisfying $k_{p_s} = 0$ to a state satisfying $k_{p_s} = 1.$ The sub-matrix A_1 (resp. A_2 and A_0) contains the state transitions from any state of $k_{p_s} = p_s$ to a state satisfying $k_{p_s} = p_s$ (resp. $k_{p_s} = p_s - 1$ and $k_{p_s} = p_s + 1).$

In the Q matrix, each diagonal element of a row is the negative sum of all other elements at the same row. In a steady-state where transitions of arrival to and departure from a state are balanced, we establish the following system of linear equations:

$$\mathbf{x}Q = \mathbf{0}. \quad (4)$$

Given the large-scale state space of the system, solving this equation for \mathbf{x} represents a challenging numerical issue. To deal with the scale of the system, we apply Neuts' Matrix-Geometric technique [19] to solve the system. In particular, we first solve

$$A_0 + RA_1 + R^2A_2 = \mathbf{0} \quad (5)$$

where R is the rate matrix, and $\mathbf{0}$ is a zero matrix with the same dimension as $A_0.$ In the numerical computation, the problem is translated into finding the minimal non-negative solution of the matrix equation given in (5). It is performed iteratively as follows:

$$-(A_0 + R(k)^2A_2)(A_1)^{-1} = R(k+1) \quad (6)$$

TABLE III
INDIVIDUAL IPTV STREAM STATISTICS

Video stream	Average arrival rate (Mbps)	Average packet size (bytes)	Erlang parameters	
			k	λ_v
ICE	0.57	825.79	2.08	171.75
CREW	0.87	926.37	2.12	260.73
HARBOUR	1.72	954.95	1.72	356.07
SOCCER	1.06	927.24	1.85	275.77
CITY	0.93	908.36	1.81	242.63

with $R(0) = \mathbf{0}$ and convergence determined by $|R(k+1) - R(k)| < \varepsilon,$ with $\varepsilon = 10^{-12},$ for example.

After that, we use

$$B[R] = \begin{bmatrix} B & C \\ E & A_1 + RA_2 \end{bmatrix} \quad (7)$$

to solve

$$(\mathbf{x}_0^s, \mathbf{x}_1^s)B[R] = (\mathbf{0}, \mathbf{0}) \quad (8)$$

with the following normalization:

$$\mathbf{x}_0^s \mathbf{e} + \mathbf{x}_1^s (I - R)^{-1} \mathbf{e} = 1 \quad (9)$$

to obtain \mathbf{x}_0^s and $\mathbf{x}_1^s,$ where \mathbf{e} is the all-one vector, and $\mathbf{x}_{k_{p_s}}^s$ is the probability vector describing the network states of k_{p_s} stations. The remaining $\mathbf{x}_i^s, i = 2, 3, \dots, PS - 1$ can be computed based on the following iteration using the rate matrix:

$$\mathbf{x}_{i+1}^s = \mathbf{x}_i^s R. \quad (10)$$

The solution \mathbf{x} for the entire system is obtained as

$$\mathbf{x} = [\mathbf{x}_0^s, \mathbf{x}_1^s, \mathbf{x}_2^s, \dots, \mathbf{x}_{PS-1}^s]. \quad (11)$$

Based on the Matrix-Geometric solution, we can obtain the steady-state probability distribution for streaming TV over the IEEE 802.11e wireless home network, and the sum of the steady-state probability distribution under no packet loss condition can be used to determine the throughput of IPTV T_n in the n -station wireless home network with n IPTV flows. The throughput of the IPTV traffic T_n in the n -station network can be computed as

$$T_n = r_v \cdot \sum_{k_{p_s}=0}^{PS-1} \sum_{k_v=0}^{V-2} \sum_{k_{p_a}=0}^{PA-1} \sum_{i=0}^{I-1} \sum_{j=0}^{J-1} x_{k_v, i, j, k_{p_s}, k_{p_a}} \quad (12)$$

TABLE IV
AGGREGATED IPTV TRAFFIC STATISTICS

Number of IPTV streams	Mix of video streams	Average arrival rate (Mbps)	Average packet size (bytes)	Erlang parameters	
				k	λ_v
1	1 ICE	0.57	825.79	2.08	171.75
2	1 ICE + 1 CREW	1.21	876.08	2.10	373.29
3	1 ICE + 1 CREW + 1 HARBOUR	2.64	901.67	1.32	496.47
4	1 ICE + 1 CREW + 1 HARBOUR + 1 SOCCER	3.36	908.58	2.05	973.37
5	1 ICE + 1 CREW + 1 HARBOUR + 1 SOCCER + 1 CITY	4.14	908.54	2.04	1205.50
6	2 ICE + 1 CREW + 1 HARBOUR + 1 SOCCER + 1 CITY	4.51	894.75	1.99	1293.19
7	2 ICE + 2 CREW + 1 HARBOUR + 1 SOCCER + 1 CITY	5.23	899.27	1.94	1453.07
8	2 ICE + 2 CREW + 2 HARBOUR + 1 SOCCER + 1 CITY	6.66	906.23	1.81	1717.05
9	2 ICE + 2 CREW + 2 HARBOUR + 2 SOCCER + 1 CITY	7.37	908.56	2.05	2146.96
10	2 ICE + 2 CREW + 2 HARBOUR + 2 SOCCER + 2 CITY	8.16	908.54	1.89	2189.60
11	3 ICE + 2 CREW + 2 HARBOUR + 2 SOCCER + 2 CITY	8.53	918.30	1.94	2365.95
12	3 ICE + 3 CREW + 2 HARBOUR + 2 SOCCER + 2 CITY	9.25	919.02	2.15	2838.83
13	3 ICE + 3 CREW + 3 HARBOUR + 2 SOCCER + 2 CITY	10.68	923.58	2.06	3129.60
14	3 ICE + 3 CREW + 3 HARBOUR + 3 SOCCER + 2 CITY	11.40	923.80	2.00	3246.43
15	3 ICE + 3 CREW + 3 HARBOUR + 3 SOCCER + 3 CITY	12.18	922.82	2.09	3617.57

where r_v is defined in (1). Equation (12) is basically computing the mean of IPTV arrival rate. In a lossless system, the number of arrivals is equal to the number departures, i.e., the throughput.

V. PERFORMANCE EVALUATION

In this section, we measure several key performance metrics of IPTV streaming over wireless home networks. Using our developed model, we first measure the system capacity highlighting the potential system support of the existing and future wireless home networks. We further perform network simulator (ns2) [20] simulations with real video streams [21] so as to validate our numerical results, and measure various important system and streaming performance including the channel capacity, packet delay and jitter, instant, and average PSNR behavior of IPTV streaming.

We use five different 4CIF video sources,¹ ICE, CREW, HARBOUR, SOCCER, and CITY, to generate the test *IPTV streams*. Each video source is of a resolution of 704×576 , and is compressed using H.264/AVC JSVM 9.8 [22] with parameters of 30 fps, a GoP of 16 frames, the quantization parameters (QPs) of 32, 34 and 35 for I, P, and B frames, respectively. The statistics parameters of the five video streams are shown in Table III.

To generate an aggregated IPTV traffic of n IPTV streams, we recursively select streams from the set of the ordered five video streams {ICE, CREW, HARBOUR, SOCCER, and CITY} and each stream begins at a random start time within the first 0.5 s of the experiment. By mixing different video streams, we simulate the common scenario that different home users watch different types of TV programs. Of course, the five test video streams can be ordered in other ways. Table IV shows the statistics of the generated aggregated IPTV traffic with different numbers of IPTV streams.

We assume the presence of a certain amount of BE traffic sent between the stations and AP. We use Poisson process [23] to model the BE traffic. While the default arrival rates, λ_{p_a} and λ_{p_s} , for the downlink and uplink BE traffic are set to 10 packets/s and 20 packets/s, respectively, with a packet size of 1024 bytes, we also consider various levels of BE traffic load.

Other parameters, I, J, PA, and V, in the proposed Markovian framework, are set to 3, 3, 3, and 10, respectively.

We study a wireless home network that implements the QoS enhancement specified in the IEEE 802.11e standard. In terms of channel data rate, we model both the IEEE 802.11b standard and the IEEE 802.11g standard operating at 11 Mbps and 54 Mbps, respectively. Moreover, since our model allows arbitrary channel data rate settings, we also consider scenarios of future wireless home networks where the wireless channel operates at a much higher data rate² such as 100 Mbps.

A. System Capacity

We first measure the system capacity in terms of the number of IPTV streams that can be supported by a wireless home network using either the IEEE 802.11b, the IEEE 802.11g, or the IEEE 802.11n standard. We show the throughput under different number of IPTV streams in Fig. 3. Numerical results are obtained by solving the corresponding CTMC using the Matrix-Geometric approach. Simulation results obtained by ns2 are included in the figure for comparison. The excellent agreement between the numerical and simulation results confirms the accuracy of our model.

It can be seen from Fig. 3 that the IEEE 802.11b standard can merely support the two IPTV streams (the aggregation of ICE and CREW shown in Table IV) and the channel becomes congested when the three IPTV streams in Table IV are transmitted. Thus, it has very limited potential to prepare for future advancements in either supporting more simultaneous IPTV streams or higher quality streams. The IEEE 802.11g standard, on the other hand, has significant improvement in the system capacity, supporting the six IPTV streams. While the channel data rate increases almost five times from 11 Mbps of IEEE 802.11b to 54 Mbps IEEE 802.11g, the capacity support of IPTV streams, which form the majority of the traffic, increases less than four times. This suggests that the system capacity of IPTV does not

²Note that when considering future higher data rate, we adopt the current practice in the standard development that future IEEE 802.11 standards are backward compatible with the existing IEEE 802.11 standard. For example, we consider that future IEEE 802.11 standards operating at 2.4 GHz must follow the existing IEEE 802.11b standard to transmit a packet, except that the transmission of the payload within a packet may be involved in an advanced transmission technology that will result in a shorter transmission duration.

¹http://nsl.cs.sfu.ca/wiki/index.php/Video_Library_and_Tools

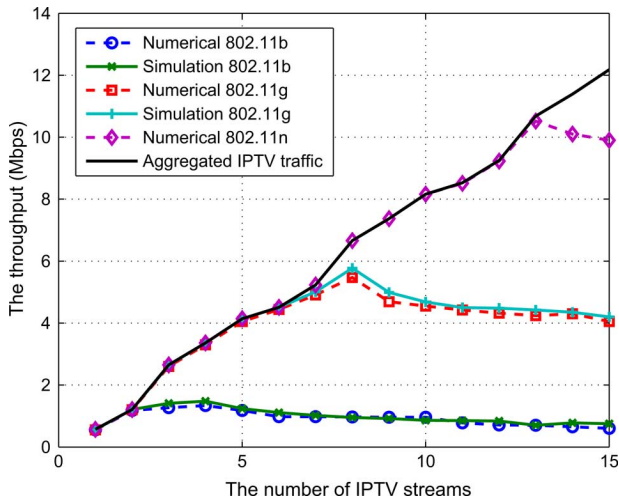


Fig. 3. IPTV throughput of different wireless home networks with default light BE traffic.

grow linearly with the data rate, which is consistent with earlier reports.

The observation of nonlinear growth of the system capacity with the channel data rate has prompted the investigation of system capacity study for future wireless home network with higher channel data rates.³ From Fig. 3, we can see that for new emerged wireless communications technologies operating at 2.4 GHz offering 100 Mbps, the system supports 13 simultaneous IPTV streams for the aggregated traffic specified in Table IV. The results suggest that the very recent development of the IEEE 802.11n standard operating at 100 Mbps already offers adequate support for the IPTV application.

Next, we investigate the impact of BE traffic on the system capacity. We vary the overall BE traffic load from 30 kbps to 2.64 Mbps, where the downlink BE traffic and the uplink BE traffic are given one third and two third of the load, respectively. Fig. 4 shows the IPTV throughput under different overall BE load. From the figure, it can be seen that in the case of streaming the two IPTV streams over the IEEE 802.11b wireless home network, as the offered load of the BE traffic reaches around 1.31 Mbps, the transmission collision intensifies and the IPTV throughput drops below a level to adequately delivery the two simultaneous IPTV streams. Likewise, in the case of streaming the six IPTV streams over the IEEE 802.11g wireless home network, a drop trend of the IPTV throughput is developed at around 0.47 Mbps of the BE traffic load. These results tell that while the IEEE 802.11e standard specifies priority delivery for video traffic, due to its contention-based design, the BE traffic can affect the delivery of IPTV video streams.

B. Delay Performance

Fig. 5(a) shows individual packet delay of the ICE video stream in the cases of streaming the two streams and the three streams specified in Table IV over IEEE 802.11b. Here, the delay measures the interval from the time when a packet arrives to the AP from the Internet to the time when the packet reaches

³Such developments are already underway with IEEE 802.11n for 100 Mbps.

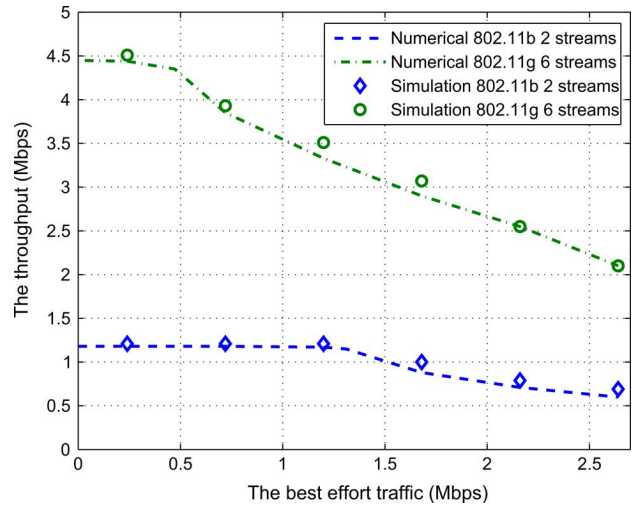


Fig. 4. IPTV throughput of the IEEE 802.11b and the IEEE 802.11g wireless home networks for a range of intensity of BE traffic.

the intended station. The limitation of the IEEE 802.11b standard for IPTV application is clearly illustrated. While the video packets suffer over 300-ms delay in the AP showing the inadequate of support of the IEEE 802.11b wireless home networks with the three simultaneous IPTV streams, the network appears to cope well in the case of streaming the two IPTV streams. We further show the cumulative distribution of delay and jitter of streaming the two IPTV streams in Fig. 6(a). As can be seen, 95% of the IPTV packets are served by the AP within 20 ms, and 94% of packet jitter is within 10 ms.

Fig. 5(b) shows individual packet delay of the ICE video stream over the time for the IEEE 802.11g wireless home network. We see that with a higher channel data rate, the wireless home network can now carry up to six simultaneous IPTV streams. With adding in the seventh IPTV stream, there is a sharp increase in packet delay. In Fig. 6(b), we show the cumulative distribution of packet delay and jitter for the case of streaming the six IPTV streams. The results report that almost all IPTV packets are served by the AP within 20 ms with delay jitter within 10 ms.

C. PSNR Performance

Fig. 7 shows the PSNR performance of the ICE video stream in both the IEEE 802.11b and the IEEE 802.11g wireless home networks operating at the critical points. The results further confirm that the IEEE 802.11b and the IEEE 802.11g wireless home networks can support the specified two and six IPTV streams, respectively, achieving an average PSNR of over 35 dB. With one more IPTV stream adding to the networks, the PSNR performance of the ICE video stream drops sharply to around 15 dB in both of the networks.

Furthermore, given a number of simultaneous IPTV streams, we compute the average PSNR observed at all receivers. Fig. 8 shows the average PSNR performances for various number of simultaneous IPTV streams over the IEEE 802.11b and 802.11g wireless home networks. Again, we observe that satisfactory average PSNR performance is achieved with the two and six IPTV

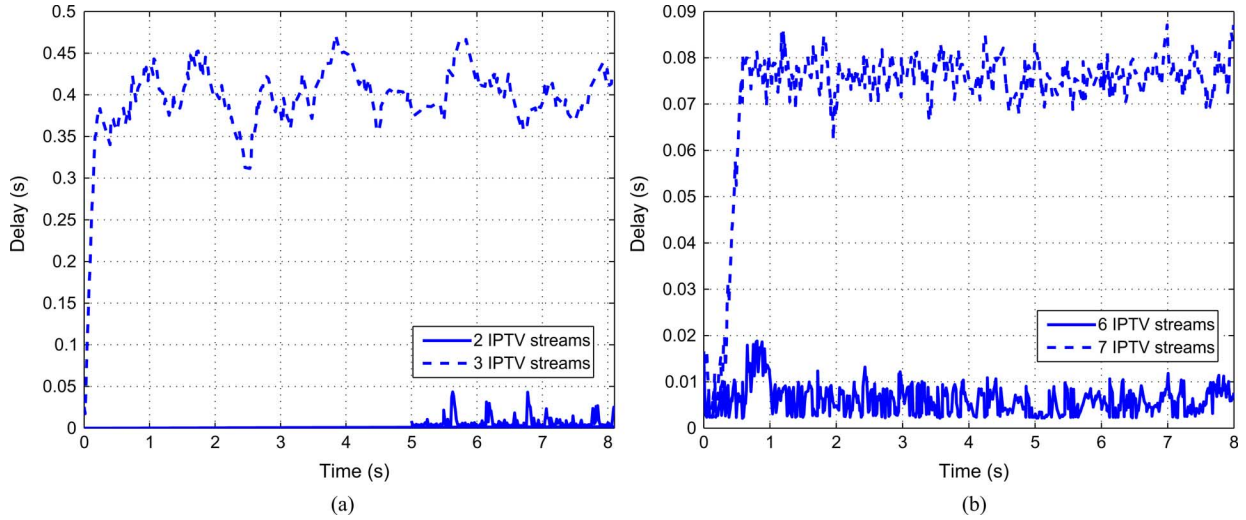


Fig. 5. Packet delay of the ICE video stream. (a) IEEE 802.11b. (b) IEEE 802.11g.

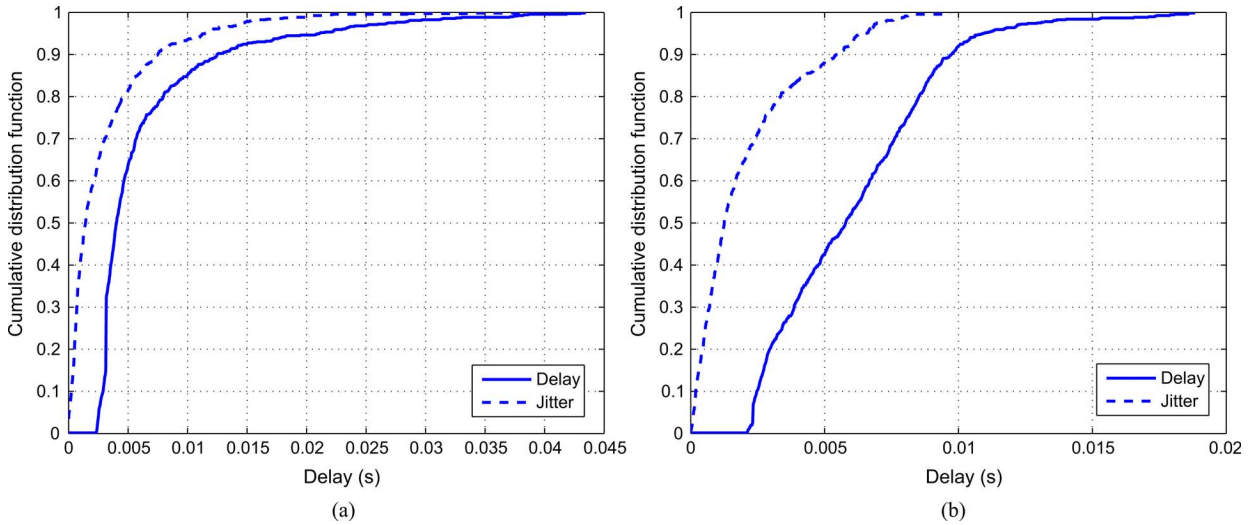


Fig. 6. Cumulative distribution function of packet delay and jitter of the ICE video stream. (a) IEEE 802.11b with two IPTV streams. (b) IEEE 802.11g with six IPTV streams.

streams for the IEEE 802.11b and IEEE 802.11g networks, respectively. When the number of IPTV streams increases, the average PSNR quickly drops indicating inadequate support. This is consistent with the capacity result illustrated in Fig. 3.

VI. CONCLUSIONS

In this paper, we studied the performance of IPTV streaming over wireless home networks. We developed a Markovian framework to model the IPTV traffic streams and the IEEE 802.11e MAC protocol. With the developed model, we investigated the system capacity, delay and jitter, and PSNR performance. Additionally, we performed simulation experiments using ns2 to validate our numerical results and further study the performance in other aspects.

Our investigation shows that in general, the IEEE 802.11b standard is insufficient to support the IPTV application while the IEEE 802.11g standard is suitable. For the particular scenario

we test, we show that IEEE 802.11b can only support up to two simultaneous IPTV streams while IEEE 802.11g supports up to six simultaneous IPTV streams. After factoring surrounding interference, distanced connection with a lower physical data rate, and higher quality, we expect that the IEEE 802.11b standard will soon appear as a bottleneck. As the demand for high-quality streaming increases, a higher speed wireless home network, such as the IEEE 802.11n standard, is required.

Besides, our study also confirms that the system capacity of IPTV in a wireless home network does not grow linearly with the data rate. While increasing the data rate of a wireless home network may represent an effective solution to increase the system capacity of IPTV, other efforts such as an efficient MAC protocol operation and QoS mechanism may also be necessary to further improve the network performance in order to achieve the future vision of pervasive personal entertainment enjoyment.

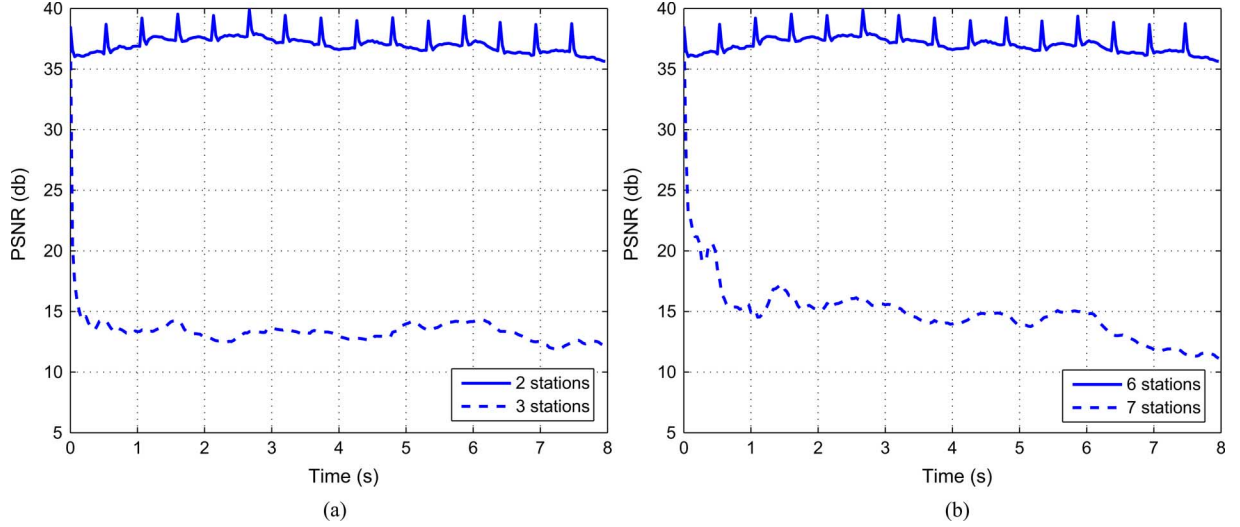


Fig. 7. PSNR performance of the ICE video stream. (a) IEEE 802.11b. (b) IEEE 802.11g.

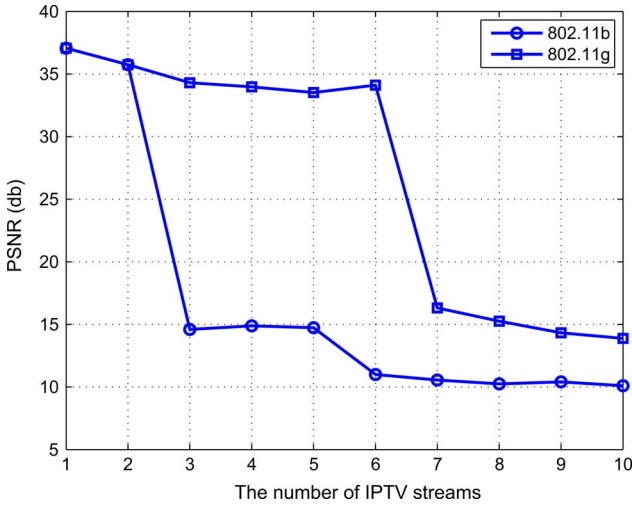


Fig. 8. Average PSNR performance in the IEEE 802.11b and IEEE 802.11g wireless home network with default light BE traffic.

TABLE V
MAC PROTOCOL SYSTEM PARAMETERS

Access category	AIFS	CW_{min}	Maximum retry limit, r	Maximum backoff stage, m
IPTV	2	7	7	4
BE	7	31	7	5

APPENDIX IEEE 802.11E SERVICE MODEL

In this Appendix, we show how to compute the channel service rate, $\mu(n)$, and the video service ratio, $\alpha(n)$. We assume that there are n IPTV flows and there exists BE traffic to be delivered in both the AP and the n stations. The MAC parameters for IPTV traffic and the BE traffic are shown in Table V.

We consider access categories (AC_c) of traffic, $c \in \{\text{IPTV or BE}\}$, and the links of a certain access category (AC) maintains its persistence probability, τ_c , to access the channel in each time-slot. We model the backoff operation of each station with a Markov chain. This model is based on the

Bianchi's work [17] with the addition of frame retransmission limit. The state i, j corresponds to the i TH backoff stage of a station and that station has j as its backoff counter. The variable i ranges from 0 as the first backoff stage to r_c as the retransmission limit. The value j ranges from 0 to $W_{c,i} - 1$, where $W_{c,i}$ is the backoff window of stage i in AC_c ; the backoff window $W_{c,i}$ is given by

$$W_{c,i} = \begin{cases} 2^i \cdot CW_{c,\min}, & 0 \leq i \leq m_c \\ 2^{m_c} \cdot CW_{c,\min} & m_c < i \leq r_c. \end{cases} \quad (13)$$

Let p_c denote the conditional collision probability, which is the probability that a frame encounters a collision when it is transmitted. Let $\alpha_{c,i,j}$ be the stationary distribution for AC_c . Owing to the chain regularities, we have

$$\begin{aligned} \alpha_{c,i,0} &= p_c \cdot \alpha_{c,i-1,0}, \quad 0 < i \leq r_c, \\ \alpha_{c,i,j} &= \frac{W_{c,i} - j}{W_{c,i}} \cdot \alpha_{c,i,0}, \quad 0 \leq i \leq r_c, 0 < j < W_{c,i}. \end{aligned} \quad (14)$$

Imposing the normalization condition, $\sum_{i,j} \alpha_{c,i,j} = 1$, we obtain

$$\alpha_{c,0,0} = \begin{cases} \frac{\xi_c}{\nu_{c,r} + \kappa_c}, & r_c \leq m_c \\ \frac{\xi_c}{\nu_{c,m} + \kappa_c + \nu_c}, & r_c > m_c \end{cases} \quad (15)$$

where

$$\begin{aligned} \xi_c &= 2(1 - 2p_c)(1 - p_c) \\ \nu_{c,r} &= W_{c,0}(1 - (2p_c)^{r_c+1})(1 - p_c) \\ \nu_{c,m} &= W_{c,0}(1 - (2p_c)^{m_c+1})(1 - p_c) \\ \kappa_c &= (1 - 2p_c)(1 - p_c^{r_c+1}) \\ \nu_c &= W_{c,0}2^{m_c}p_c^{m_c+1}(1 - 2p_c)(1 - p_c^{r_c-m_c}) \end{aligned} \quad (16)$$

and n_c denotes the number of stations belonging to different AC s, r_c and m_c are the maximum retry limit and the maximum backoff stage, respectively, and $W_{c,0}$ is the minimum backoff window size for AC_c . The maximum backoff stage describes the maximum number that the contention window may double

counting from CW_{\min} , and this number is capped at the retry limit.

The probability τ_c that a station of AC_c transmits in a slot time is given by

$$\tau_c = \sum_{i=0}^{\tau_c} \alpha_{c,i,0} = \frac{1 - p_c^{\tau_c+1}}{1 - p_c} \alpha_{c,0,0}. \quad (17)$$

The probability τ_c depends on the collision probability p_c which is given by

$$p_c = 1 - (1 - \tau_c)^{n_c-1} \prod_{x \neq c} (1 - \tau_x)^{n_x}. \quad (18)$$

Thus, the throughput is given by

$$S_c = \frac{P_{c,S} T[P]_c}{T[ST]} \quad (19)$$

where $P_{c,S}$ is the probability that a slot contains a successful transmission which is given by

$$P_{c,S} = n_c \tau_c (1 - \tau_c)^{n_c-1} \prod_{x \neq c} (1 - \tau_x)^{n_x}. \quad (20)$$

The probability that a slot time is idle is P_I , $P_I = \sum_c (1 - \tau_c)^{n_c}$. The probabilities P_C that a slot time contains a collision is $P_C = 1 - P_I - P_S$, where $P_S = \sum_c P_{c,S}$. $T[P]_c$ is the average time length of the frame payload of AC_c . It depends on the channel data rate R and the frame payload size L_c . $T[ST]$ is the average length of a time slot and the value $T[ST]$ is computed by $T[ST] = P_I \sigma + P_S T_S + P_C T_C$, where σ is the length of a slot time, T_S is the average length of a successful transmission slot, and T_C is the average length of a collision slot. Their numerical values can be obtained based on the computation given in [18].

Finally, the $\alpha(n)$ can be calculated by

$$\alpha(n) = \frac{S_{IPTV}(n)}{S_{IPTV}(n) + S_{BE}(n)}. \quad (21)$$

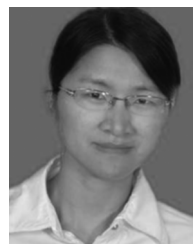
The service rate $\mu_c(n)$, depending on the channel data rate and the frame payload size, can be computed as $\mu(n) = \sum_c \mu_c(n)$ (packets/s), where

$$\mu_c(n) = \frac{R \cdot S_c(n)}{L_c}. \quad (22)$$

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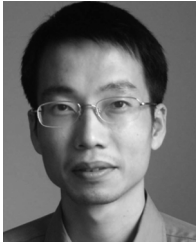
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