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Performance Evaluation of the TFD-capable Dynamic QoS Assurance of HD Video Streaming in Well-dimensioned Network

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***Abstract*—The Traffic Flow Description (TFD) option of the IP protocol is an experimental option, designed by the Authors and described by the IETF's Internet Draft. This option was intended for signalling for QoS purposes. Knowledge about forthcoming traffic (such as the amount of data that will be transferred in a given period of time) is conveyed in the fields of the option between end-systems. TFD-capable routers on a path (or a multicast tree) between the sender and receiver(s) are able to read this information, process it and use it for bandwidth allocation. If the time horizons are short enough, bandwidth allocation will be performed dynamically. In the paper a performance evaluation of an HD video transmission QoS assured with the use of the TFD option is presented. The analysis was made for a variable number of video streams and a variable number of TCP flows that compete with the videos for the bandwidth of the shared link. Results show that the dynamic bandwidth allocation using the TFD option better assures the QoS of HD video than the classic solution, based on the RSVP protocol.**

***Keywords*—Quality of service assurance, Performance evaluation, HD video streaming, Heterogeneous IP network, Traffic flow description option**

I. Introduction

THE well-known definition of quality of service (QoS), given by the International Telecommunication Union (ITU), goes: "the collective effect of service performances which determine the degree of satisfaction of a user of the service" [16]. In other words, the performance of a network that gives QoS guarantees should be great enough to satisfy user's needs. In practice user's needs may be unlimited, so the QoS assurance must focus on achieving parameters of transmission that, in the users mean opinion, are satisfactory.

QoS assurance is based on reservations of network resources, which may be dynamic (resource allocation that changes over time, according to current requirements of QoS-protected transmission) or static (one resource allocation for the whole transmission). However, regardless of its dynamics, resource allocation needs both knowledge about QoS-protected data stream flow (instantaneous in the case of dynamic allocations, statistical in the case of static ones) and a method for its distribution to intermediate nodes.

Classic methods of knowledge delivery, such as Differentiated Services (DiffServ [17]) Code Point [18] or Resource Reservation Protocol (RSVP) use channel-associated signalling (CAS), where knowledge about forthcoming traffic is transmitted along the same path or tree as the QoS-assured data. In the case of the DSCP, it is transmitted inside IP packets (in-band signalling), and in the case of RSVP in separate RSVP packets (out-of-band signalling). The above methods of signalling can only be used for static QoS assurance, absolute in the case of the RSVP and relative in the case of DiffServ.

The aim of the article is to show a comprehensive approach to the performance evaluation of High Definition (HD) [19] video transmission that was dynamically QoS-protected using the Traffic Flow Description (TFD) option of the Internet Protocol (IP). The TFD option offers in-band CAS that can be basis of both dynamic and static absolute QoS assurance. The article summarizes and extends results shown in papers [1] and [2], where two extreme cases (one HD video stream competes for bandwidth with $K = 1, 2, 3$ TCP flows and $N = 1, 2, ..., 10$ HD video streams compete for bandwidth with $K = 10$ TCP flows [2]) were discussed.

The rest of this paper is organized as follows. The second Section describes the TFD option. The third Section presents details of experiments carried out, while the fourth Section discusses results of these experiments. The fifth Section includes related work and the six Section concludes the paper.

II. Related work

In recent years, there has been a lot of work studying how to improve the efficiency of resource allocation for QoS transmissions of video (or more generally the QoS transmission of multimedia). Static allocation of resources results in wasted network resources [24][26]. Therefore, many propositions for the dynamic allocation of resources have been formulated.

In many of these propositions Software Defined Networking (SDN) is employed as an important part of QoS provisioning [21][22][23][26]. In the SDN network there are several strategies to implement QoS [23][26]. Various traffic engineering methods for QoS in SDN can be found in [21] and [23]. In [22] the SDN based dynamic rerouting of QoS traffic which includes scalable encoded videos with two QoS levels was proposed. Tekalp et al. [26] proposed an on-line compute dynamic resource allocations in a SDN network using a heuristic group-constrained shortest path (GCSP) procedure.

In mobile broadband networks, like LTE, resources are allocated by resource management (RRM) algorithms using a

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Call Admission Control (CAC). Mohammed et al. [24] show that usage of a static CAC algorithm is a waste of resources. To solve that problem Mohammed et al. [24] proposed a dynamic QoS-Aware CAC. Hwang et al. [25] proposed a QoS-aware bandwidth allocation based on a prediction provided by general regression neural networks (GRNNs). The algorithm presented in [25] can be applied to dynamic QoS management of heterogeneous home networks. Chitimalla et al. [27] proposed to optimize the quality of experience (QoE) for video transmission using application-aware resource-allocation in Ethernet passive optical network (EPON). All QoE procedures are implemented in mobile and fixed SDN controllers [27].

Banchuen et al. [28] proposed to use the Packet Pair technique to discover the characteristics of bandwidth and end-to-end delay between two video conference clients. On the basis of the obtained results paths are set up dynamically in the SDN network. Atawia et al. [29] proposed extensions to existing Predictive Resource Allocation (PRA) schemes. A Robust Green Predictive Resource Allocation (R-GPRA) adopts stochastic programming methods to provide allocation over the time horizon which trades-off between energy-saving and the risk of wasting resources [29]. The proposal in the [29] solution can be used for Dynamic Adaptive Streaming over HTTP (DASH).

Wei et al. [30] proposed a cloud-based online video transcoding (COVT) system which optimize usage of cloud resource usage during QoS-aware online video transcoding. Another system for the cloud was proposed by Alasaad et al. [31] which is based on a Prediction-Based Resource Allocation algorithm (PBRA). Armentia et al. [32] proposed mechanisms for QoS flexibility demands in multimedia applications using the multi-agent based middleware which adjusts the resource demands of the applications to the resource availability. Xu et al. [33] proposed an event driven resource provisioning framework which guarantees the QoS in the cloud for MapReduce computations. Mendiola et al. [34] proposed to use a SDN for dynamically provide L2 services with QoS requirements over a DOCSIS access networks by a QoS-enabled pipes.

III. Traffic Flow Description

The TFD option consists of five fields (Fig. 1), starting with two 8-bit option control fields, a 16-bit Flags field, and ending with two 32-bits fields intended to convey knowledge about forthcoming traffic [5].

A. Control fields

Depending on the version of the IP protocol, the first field contains the Option Type field (Fig. 1b) or a sequence of three bits followed by a five-bit binary number (Fig. 1a). The first bit of the IPv4's sequence is set, which means that after the fragmentation of an IP packet all fragments must carry the option. The next two bytes are clear, denoting an option for control purposes. The unknown five bytes (symbolized by string of five signs x) is the option number, which will be allocated by the Internet Assigned Numbers Authority (IANA). The IPv6's Option Type field has a similar structure. The first three bits of the field are clear, denoting a control option that should be skipped if TDF-incapable routers don't recognize it, and that routers cannot change values stored in the option's fields. The last five bits is the option number, allocated by IANA.

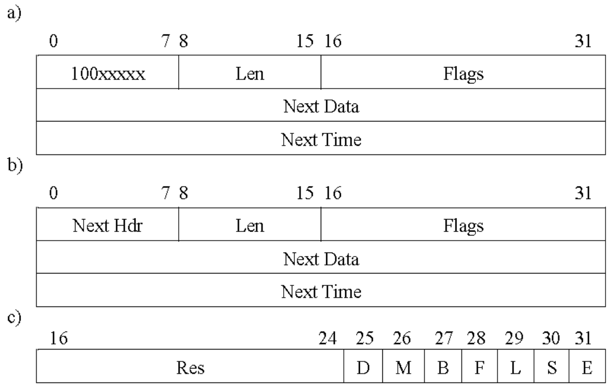

Fig. 1. IP Traffic Flow Description option [n5]: a) IPv4, b) IPv6, c) Flags

The second control field, named Opt Data Len (Fig. 1b) or Len (Fig. 1a), contains the length of the option, calculated excluding (IPv6) or including (IPv4) two option control fields. Thus, the value of this field is equal to 10 (IPv6) or 12 (IPv4).

B. Knowledge about forthcoming traffic

The two option control fields are followed by option-specific data. In the case of the TFD option, the option data are divided into three fields: Flags, Next Data and Next Time (Fig. 1). The Next Data contains the amount of data (given in bytes) that will be transmitted in the near future. The time horizon, in which knowledge about forthcoming traffic is acquired, is stored in the Next Time field. The times stored in the Next Time field are stated in milliseconds. The ratio of the Next Data to the Next Time is an estimated value of the bit rate of forthcoming traffic.

The value of the Next Time field is a planning horizon for quality of service management system. In the case of long planning horizons, allocation of network resources will be made in a static manner. Short planning horizons result in dynamic resource allocation. Note that if the planning horizon is too short, the system will lose the opportunity for prior resource allocation and becomes a follow-up system.

The planning horizon, conveyed in the Next Data field, can be constant [1][2][6] or variable [7][8]. In all experiments shown in this paper, the planning horizon is constant and the Next Time field is set to 300 ms.

C. Source of knowledge and accuracy of bit rate estimates

The accuracy of the bit rate estimate depends on the source of the knowledge. Knowledge gained from the analysis of the encoding video is accurate while knowledge obtained from the traffic predictor is merely approximate. Because information about the potential accuracy of the traffic description may be useful for QoS management systems, the source of knowledge of forthcoming traffic is coded using B (as buffer) and F (as forecasting) bits of the Flags field (Fig. 1c).

When the B bit is set and the F bit is clear then this denotes that the knowledge was gained from analysis of the sending buffer. When the B bit is clear and the F bit is set then this denotes that the knowledge was obtained from the traffic predictor. When both bits are clear then this denotes that the knowledge does not come from either buffer analysis or from forecasting, but directly from the video encoder. The sequence of the B and F bit set is denied. The best accuracy is achieved when simple analysis of the encoding video (stored in the sending buffer or newly encoded) is complemented by the detection of scene changes and traffic estimations are performed within scenes [7][8]. However, this method, based on a variable time horizon, is more time-consuming (and, generally, resource-consuming) than using the constant planning horizon.

D. The other bits of the Flag fields

The other bits of the Flag fields are (Fig. 1c): D (as data), M (as maximum), L (as large), S (as stream) and E (as elastic). The D bit specifies the format of the number conveyed in the Next Data field. If the D flag is set, the Next Data field contains a floating-point value. Otherwise it contains a positive integer value (unsigned integer). The M flag informs intermediate systems that the Next Data field is maximum now (in the scale of a single transmission). The L flag indicates that a large amount of data is transmitted (large file, video, etc.). The last two flags, S and E, denote the transmission of stream (inelastic) and elastic traffic, respectively. The rest of the 16-bit Flags field is unused (reserved for future use).

IV. Experiments

This section describes the test environment, the real and emulated part of the test network, the test video sequences and the method of creation of the test video stream, and the organization of the experiments (including the scenarios of the emulation experiments).

A. Overview of the test environment

Experiments were performed in a mixed (real and emulated) network environment, depicted in Fig. 2. The emulated fragments of the network are marked in gray in Fig. 2. The real network was build using Gigabit Ethernet technology, and the emulated network also worked at 1 Gbps. The use of the throughput of 1 Gbps enables simultaneous, lossless transmission of 10 HD video streams.

The real equipment consists of a group of servers $(SM_1, ..., SM_N, STCP_1, ..., STCP_K)$ and receivers $(RM_1, ..., RM_N, RTCP_1, ..., RTCP_K)$ connected to the emulation servers (directly or through a non-blocking, gigabit switch). Servers and receivers were built on the basis of high performance PCs. These computers were equipped with an Intel multicore processor, 16 GB of RAM memory, and a Gigabit Ethernet card. The emulation server was equipped with two Intel Xeon processors and six Gigabit Ethernet interfaces. Two of the network interfaces were mounted on the motherboard, four on two dual Gigabit Ethernet cards.

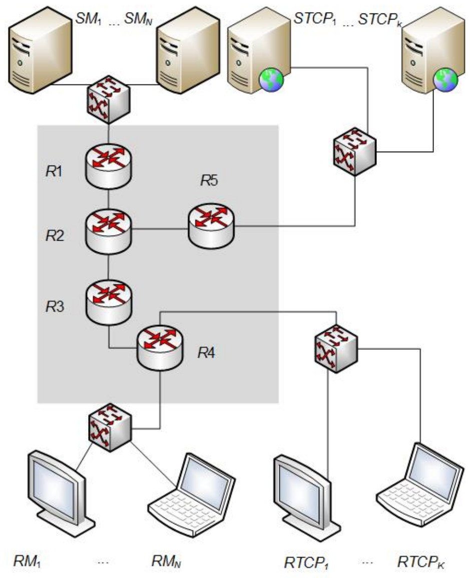

Fig. 2. Test environment

The foreground traffic was generated using test HD video clips, described below. Video transmission were carried out using the Real-time Transport Protocol (RTP) working on a top of the User Datagram Protocol (UDP). As the background traffic, bulk data conveyed in packets of the Transmission Control Protocol (TCP) were used.

B. Emulated part of the test network

The emulated part of the network is used for the implementation of dynamic reservations with the use of TFD signalling. For the sake of comparison, static reservations using the RSVP signalling protocol, as well as best effort transmissions, were carried out in the emulation environment. The emulation environment was remotely managed. The build-in interface of the emulation server was used for the management of the emulation experiment, while interfaces mounted on additional network cards were used for transmission of foreground and background traffic in the test network. The management network is not presented in Fig. 2.

To emulate routers R1 to R5 and connections inside the gray block in Fig. 2, the Berkeleys ns-2 simulator, running in emulation mode, was used [11]. The original ns-2 software was supplemented by improvements developed at the University of Magdeburg (Germany) [12][13]. The most important of these improvements concerns the real-time scheduler and cooperation with a real network. The software has also been supplemented by the extension [3], made by the Authors, which uses the flexible mapping of incoming and outgoing traffic to allow the ns-2 to use an external switch as a traffic expander. As a result, the emulator is able to serve more end-systems or subnetworks than is indicated by the number of interfaces of the emulation server.

C. Real part of the test network

The real equipment consists of a set of video (media) servers, a set of TCP servers, a set of video and TCP receivers, and high-performance switches. Media servers (SM in Fig. 2) are built on the basis of the VLC [14] software tool. The Linux version of the VLC was used for all experiments. The use of the TFD option requires some information from the sending application (the number of data that will be sent in the next period of time, the value of this period of time, and some binary information conveyed in the Flags field), so the original VLC media player was extended by our modules that support the TFD option. Media receivers (RM in Fig. 2) also use the VLC software tool.

The TCP servers (STCP in Fig. 2) are build on the basis of the iPerf tool [15]. This is the open-source software that allows one to measure performance of TCP, UDP and Stream Control Transmission Protocol (SCTP) connections. During experiments, the iPerf was used both as a traffic generator that emulates the transmission of bulk data and as TCP receiver (RTCP in Fig. 2).

Both VLC and iPerf were run on the Linux operating system. To enable TFD-based signalling, the Linux kernel was extended by the implementation of the TFD option [4].

As with the emulated part of the network, SM and STCP servers were managed using dedicated links (not depicted in Fig. 2).

D. Test sequences

All HDTV test video sequences, used in our experiments, were imported from an external source [9]. These video sequences are owned by NTIA/ITS, an agency of the U.S. Federal Government. They were created under Project Number 3141012-300, Video Quality Research, in 2008.

The collection [9] of video sequences, publicly available at The Video Quality Experts Group (VQEG) site, consists of 8 clips. There are (in alphabetical order): Aspen, ControlledBurn, RedKayak, RushFieldCuts, SnowMnt, SpeedBag, TouchdownPass and WestWindEasy. Each clip includes full high definition (1920 x 1080) native video with a frame rate of 30 frames per second [10]. The compression and coding of the hvideo material was made according to the H.264 standard. As with experiments shown in [2], the tests that were chosen contained sequences with the target bit rate of the video streams set to 40 Mbps (the maximum for Blu-ray). Each clip is 19 seconds long.

The single video stream, used in the experiments, is made of all 8 video clips, put together in a single video sequence lasting for 2 minutes and 32 seconds. To avoid the influence of an individual video clip, as well as to avoid the effect of the synchronization of video clips in a shared link, the clips appear in the video stream in random order and the transmission of each clip starts from a randomly chosen moment.

E. Organization of experiments

Experiments were organized in a similar way as in the papers [1] and [2]. The variable number of video streams $N, N = 1, 2, ..., 10$, competes for bandwidth of the shared link with K simultaneously transmitted TCP flows, $K = 0, 1, ..., 10$. Because of the assumption of a well-dimensioned network, any loss of packets during video transmission should result only from congestion, so packet error rates (PER) observed for the transmitted video should be equal to zero when K=0. It has been experimentally determined that this assumption is correct.

Four emulation scenarios, from s1 to s4, were developed and then applied to the experiments. In the first s1 scenario, the transmission of N video streams were conducted without any QoS guarantees, i.e. using the typical best effort service of the IP protocol. In the case of s2 and s3 scenarios, quality of service guarantees were assured with the use of the signalling based on the RSVP protocol. The scenarios offer both medium-dimensioned (s2) and well-dimensioned, overestimated (s3) static reservations, made according to 150% (s2) or peak (s3) of target bit rate. The s4 scenario offers dynamic reservations. QoS guarantees were assured with the use of the TFD option of the IP protocol.

Transmissions of K TCP flows were carried out using best effort service. No QoS guarantees were assured

V. RESULTS

The performance of the TFD-capable dynamic resource allocation was tested for a different number of simultaneously transmitted HD video streams ($N = 1, 2, ..., 10$), and at different levels of network load, where the level of network load was considered as proportional to the number of TCP flows ($K = 1, 2, ..., 10$) that compete for bandwidth with HD video streams in the shared link. The performance evaluation of TFD-capable dynamic QoS assurance of HD video streams was carried out using four parameters: packet error rate of the video stream (Table 1), overall video throughput (Table 2), overall TCP throughput (Table 2), utilization of the shared link (Table 1).

To avoid the influence of an individual video clip on the performance of a QoS management system, each experimental test was repeated 20 times and parameters used for evaluation were averaged.

A. Reducing the packet error rate of HD video

Packet error rate of video stream is presented in the Table 1. If number of competing TCP streams $K = 0$, video transmission is lossless ($PER = 0$), what confirms that the test network is well-dimensioned for HD video transmission.

In the case of the best-effort service of the IP protocol (the s1 scenario), packet error rates ranges from 0.11 percent ($K = 1, N = 10$) to 26.9 percent ($K = 10, N = 1$). In general, for a given number of HD video streams N, the greater the number of TCP flows K in the shared link, the greater the PER. If $K <= 6$, the PERs of the HD video traffic are under the 5-percent limit of user acceptability. If $K >= 9$, the PERs of HD videos are above that limit. If $K = 7$ and $K = 8$, the video transmission is acceptable only for larger values of N.

The use of static reservations significantly reduced the PERs. Medium dimensioned reservations (s2) put the HD video PERs under the limit of 5%. PERs include results between 0.03 and 3.5 percent. But even the overestimated reservations (s3) are still not able to assure lossless transmissions. PERs range from 0.02 to 0.49 percent.

TABLE I
PACKET ERROR RATE OF VIDEO STREAM AND LINK UTILIZATION

	packet error rate [%] of video stream										link utilization [%]									
	N																			
K	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
scenario s1																				
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.3	12.7	19.6	25.2	33.2	41.5	46.4	52.8	56.5	62.2
1	0.16	0.17	0.19	0.21	0.19	0.18	0.17	0.14	0.12	0.11	83.4	84.3	86.5	87.4	88.2	88.4	89.9	91.0	90.8	94.4
2	0.22	0.31	0.35	0.40	0.57	0.63	0.62	0.60	0.48	0.35	90.9	90.8	91.7	93.1	91.8	92.6	94.2	93.4	94.3	97.7
3	0.51	0.67	0.77	0.89	0.90	0.79	0.75	0.76	0.76	0.76	96.9	95.3	97.6	97.2	97.1	97.6	97.1	96.8	96.3	98.9
4	1.11	1.34	1.35	1.38	1.39	1.39	1.24	1.21	1.09	0.98	98.1	97.1	96.5	96.9	96.6	97.8	98.5	97.1	96.4	99.0
5	2.26	2.32	2.44	2.49	2.51	2.48	2.47	2.01	1.45	1.22	98.2	97.1	98.0	96.8	96.3	98.0	98.0	97.4	97.3	99.5
6	3.56	3.53	3.33	3.33	3.31	3.21	3.01	2.78	2.27	1.98	98.8	97.1	99.4	98.6	98.8	97.8	97.1	97.6	97.2	99.8
7	7.22	6.24	5.98	5.45	5.11	4.96	4.31	3.89	2.99	2.45	98.7	99.1	95.8	96.9	96.5	96.0	97.3	96.9	95.9	98.8
8	9.11	8.22	7.92	7.34	6.97	6.37	5.67	5.11	4.88	4.11	99.0	96.0	96.8	96.2	96.4	96.2	97.5	94.8	94.9	97.6
9	12.9	9.24	8.45	7.97	7.55	7.22	6.89	6.32	5.78	5.33	98.4	96.0	96.0	96.1	95.8	96.1	96.3	95.2	94.9	97.1
10	26.9	15.5	10.5	9.11	6.69	6.08	5.24	5.08	5.09	6.22	96.9	98.7	99.1	98.3	96.8	96.0	99.5	97.7	97.9	99.1
scenario s2																				
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.3	12.7	19.6	25.2	33.2	41.5	46.4	52.8	56.5	62.2
1	0.03	0.03	0.03	0.04	0.05	0.05	0.06	0.09	0.16	0.39	80.1	81.9	81.9	84.1	83.3	86.6	87.3	87.9	87.0	89.2
2	0.06	0.06	0.02	0.03	0.04	0.05	0.06	0.09	0.16	0.57	87.2	87.9	85.6	87.7	90.1	90.1	91.4	92.0	90.0	91.9
3	0.28	0.30	0.31	0.32	0.32	0.40	0.60	0.92	0.45	0.78	93.0	92.5	92.5	91.9	93.4	92.7	95.3	94.3	92.0	93.8
4	0.62	0.69	0.69	0.61	0.63	0.72	0.85	0.93	0.99	1.02	94.1	92.8	92.4	93.5	93.4	93.4	95.9	93.7	92.7	93.6
5	0.97	0.78	0.75	0.72	0.71	0.69	0.75	0.76	0.95	1.11	94.3	92.7	92.2	94.2	94.9	93.3	95.9	93.7	93.3	93.5
6	1.03	1.23	1.11	1.06	1.07	1.03	1.23	1.45	1.78	1.34	94.9	94.4	93.3	95.3	94.5	94.8	96.2	94.3	93.0	94.3
7	1.18	1.45	1.52	1.49	1.42	1.39	1.32	1.55	1.85	1.44	95.0	93.2	94.5	95.0	93.3	93.6	95.3	93.6	92.5	93.9
8	1.22	1.49	1.53	1.52	1.49	1.51	1.55	1.64	1.92	1.54	95.4	94.3	94.2	94.0	93.8	93.8	95.3	94.4	92.4	94.6
9	1.33	1.74	1.77	1.67	1.45	1.33	1.35	1.43	2.01	1.78	95.4	95.5	92.4	95.5	95.6	94.9	95.1	93.7	92.7	94.6
10	1.58	3.50	2.07	1.99	1.40	1.06	1.18	1.12	2.11	2.03	94.4	96.9	95.6	95.6	95.8	95.7	97.8	94.4	93.6	95.4
scenario s3																				
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.3	12.7	19.6	25.2	33.2	41.5	46.4	52.8	56.5	62.2
1	0.02	0.02	0.02	0.03	0.04	0.05	0.07	0.08	0.09	0.11	78.7	79.6	75.4	79.5	82.1	85.2	86.6	85.9	84.4	88.9
2	0.06	0.06	0.06	0.06	0.08	0.08	0.08	0.09	0.13	0.14	85.8	85.3	82.9	86.9	87.4	90.5	90.5	89.6	86.6	90.9
3	0.03	0.03	0.05	0.07	0.08	0.08	0.09	0.10	0.13	0.17	91.4	91.3	87.4	91.2	90.5	92.7	93.0	92.8	88.6	93.7
4	0.05	0.06	0.07	0.08	0.09	0.09	0.09	0.10	0.15	0.18	92.5	91.4	87.8	91.4	91.7	94.6	95.1	92.4	88.6	94.3
5	0.07	0.08	0.09	0.09	0.10	0.10	0.11	0.12	0.16	0.18	92.7	92.9	88.2	91.5	93.4	94.7	94.1	93.2	89.0	94.0
6	0.09	0.12	0.13	0.14	0.14	0.15	0.15	0.16	0.18	0.20	93.4	94.7	88.5	91.3	93.0	95.1	95.3	92.5	89.3	93.8
7	0.11	0.12	0.13	0.14	0.15	0.17	0.17	0.18	0.19	0.21	93.5	91.8	88.8	91.8	93.4	93.6	95.2	92.8	89.8	94.4
8	0.15	0.16	0.17	0.17	0.17	0.18	0.18	0.19	0.20	0.21	93.9	94.5	89.4	92.8	92.4	95.4	95.3	93.9	89.0	93.6
9	0.19	0.20	0.21	0.23	0.26	0.30	0.33	0.31	0.32	0.34	93.9	93.3	87.6	91.4	93.8	95.3	95.5	93.4	89.5	94.1
10	0.18	0.27	0.18	0.20	0.26	0.31	0.37	0.40	0.47	0.49	93.8	96.3	90.0	92.2	94.8	95.1	96.6	94.5	89.7	95.1
scenario s4																				
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.3	12.7	19.6	25.2	33.2	41.5	46.4	52.8	56.5	62.2
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	80.7	83.0	81.4	83.0	84.6	87.5	89.2	87.8	89.2	91.9
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	88.0	89.8	86.8	90.4	90.7	91.5	93.5	91.5	92.5	94.9
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	93.7	92.0	91.0	94.3	95.3	94.2	96.2	95.0	93.9	96.9
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	94.9	94.0	93.3	94.0	95.1	94.6	96.6	94.6	94.5	97.5
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	95.1	93.4	92.9	94.4	95.3	95.0	97.6	95.2	94.9	97.5
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	95.8	95.2	93.9	95.5	95.6	96.8	97.6	94.8	96.1	97.0
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	95.9	94.0	94.4	94.4	97.0	96.6	97.9	95.1	96.1	97.4
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	96.3	96.8	95.0	95.2	96.8	97.2	97.8	96.4	95.1	97.9
9	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.04	96.4	94.6	93.6	94.7	95.9	97.2	96.8	95.0	95.4	98.1
10	0.00	0.03	0.03	0.02	0.04	0.02	0.03	0.03	0.06	0.07	96.4	98.8	96.8	98.3	98.1	98.1	99.2	97.2	97.1	99.0

TABLE II
OVERALL VIDEO THROUGHPUT AND OVERALL TCP THROUGHPUT

	overall video throughput [Mbps]										overall TCP throughput [Mpbps]									
	N																			
K	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
scenario s1																				
0	63	127	196	252	332	415	464	528	565	622	0	0	0	0	0	0	0	0	0	0
1	62	127	196	251	331	414	463	527	564	621	772	722	670	618	543	480	444	381	352	325
2	62	127	195	251	330	412	461	525	562	620	847	790	731	677	603	532	487	422	375	346
3	62	126	194	250	329	412	461	524	561	617	907	837	762	720	643	565	520	450	407	382
4	62	125	193	249	327	409	458	522	559	616	919	831	782	722	649	562	522	456	406	373
5	61	124	191	246	324	405	453	517	557	614	921	854	789	719	649	579	519	446	405	374
6	60	123	189	244	321	402	450	513	552	610	928	872	784	735	656	573	530	460	414	393
7	58	119	184	238	315	394	444	507	548	607	929	860	791	738	646	566	522	462	423	392
8	57	117	180	234	309	389	438	501	537	596	933	865	789	752	656	577	525	462	416	387
9	50	113	176	228	302	379	432	495	533	590	934	861	807	740	667	574	537	457	420	391
10	34	97	171	215	285	366	444	506	548	591	935	890	820	768	683	594	551	471	431	400
scenario s2																				
0	63	127	196	252	332	415	464	528	565	622	0	0	0	0	0	0	0	0	0	0
1	62	127	196	252	332	415	464	528	564	620	738	665	623	588	501	449	417	358	307	271
2	62	127	196	252	332	415	464	528	564	618	810	760	685	642	563	486	456	381	343	301
3	62	127	195	251	331	413	461	523	562	617	867	802	716	665	610	515	483	413	371	326
4	62	126	195	250	330	412	460	523	559	616	879	825	729	674	604	522	490	410	377	322
5	62	126	195	250	330	412	461	524	560	615	881	800	716	686	611	520	495	428	368	322
6	62	125	194	249	328	411	458	520	555	614	887	813	730	704	625	540	509	417	367	325
7	62	125	193	248	327	409	458	520	555	613	888	816	750	687	610	524	496	428	380	324
8	62	125	193	248	327	409	457	519	554	612	892	826	728	685	625	535	511	428	368	327
9	61	125	193	248	327	409	458	520	554	611	893	809	736	702	621	527	512	433	379	333
10	50	121	191	234	322	402	459	505	548	612	894	848	765	722	636	555	519	439	388	342
scenario s3																				
0	63	127	196	252	332	415	464	528	565	622	0	0	0	0	0	0	0	0	0	0
1	62	127	196	252	332	415	464	528	564	621	725	682	560	562	505	444	398	337	274	270
2	62	127	196	252	332	415	464	528	564	621	795	738	618	614	554	483	443	369	298	294
3	62	127	196	252	332	415	464	527	564	621	852	804	666	660	580	504	479	401	329	311
4	62	127	196	252	332	415	464	527	564	621	863	796	670	650	591	521	475	407	324	320
5	62	127	196	252	332	415	464	527	564	621	865	808	677	670	589	512	486	402	331	317
6	62	127	196	252	332	414	463	527	564	621	871	816	674	671	601	531	477	413	332	324
7	62	127	196	252	331	414	463	527	564	621	872	819	674	674	593	529	491	401	335	316
8	62	127	196	252	331	414	463	527	564	621	876	819	679	661	602	537	497	400	336	321
9	62	127	196	251	331	414	462	526	563	620	877	824	693	655	598	522	488	407	326	327
10	60	125	191	232	326	404	460	525	554	619	878	838	709	690	622	547	506	420	343	332
scenario s4																				
0	63	127	196	252	332	415	464	528	565	622	0	0	0	0	0	0	0	0	0	0
1	63	127	196	252	332	415	464	528	565	622	745	687	630	575	518	461	420	361	325	297
2	63	127	196	252	332	415	464	528	565	622	817	749	677	644	564	506	469	397	350	317
3	63	127	196	252	332	415	464	528	565	622	875	818	720	681	613	526	499	419	387	339
4	63	127	196	252	332	415	464	528	565	622	887	819	727	709	618	537	496	417	383	347
5	63	127	196	252	332	415	464	528	565	622	888	832	747	697	609	548	515	431	396	358
6	63	127	196	252	332	415	464	528	565	622	895	837	748	706	612	539	507	422	384	355
7	63	127	196	252	332	415	464	528	565	622	896	823	752	700	638	542	519	424	391	348
8	63	127	196	252	332	415	464	528	565	622	900	835	755	697	618	558	509	426	386	357
9	62	127	196	252	332	415	464	528	565	622	901	849	743	702	624	556	503	424	393	349
10	62	127	196	252	332	415	464	528	565	622	902	861	772	731	649	566	528	444	406	368

Zero PERs (rounded to two decimal places) were observed only when dynamic reservations, based on the TFD options, were used. $PER = 0$ here was obtained for almost all tested cases. Only in extreme cases of $K = 10$ or $N = 10$, and if $K = 9$ and $N > 5$, nonzero PERs were achieved. The minimum observed nonzero PER was 0.01% and the maximum was 0.07%.

B. Reducing the impact of the TCP aggressiveness

Fig. 3 depicts chosen HD video packet error rates as a function of the number of HD video streams in the shared link. Using common sense, for a given number of TCP flows K, enlarging the number of video streams N should result in increased PERs. Fig 3a shows the opposite trend - the larger the N, the smaller the PER. For a given K, an increase of N causes a reduction of the PER. This trend (particularly evident if the number of TCP flows that compete for bandwidth in a shared link is larger than 7) is caused by the aggressive nature of the modern TCP.

The TCP, due to its sensitive congestion control, is regarded as a very gentle protocol, which requires TCP-like behaviour from the other protocols in the shared link. These protocols should be TCP-friendly [20], i.e. should behave under congestion in the same way as the TCP. However, if the best effort service is used and percentage amount of video is too small, the TCP-unfriendly RTP was not able to effectively compete for bandwidth with the TCP.

The use of any method of resource allocation allows the impact of TCP aggressiveness on HD video traffic to be minimized and reverses this trend. Graphs depicted in Fig. 3b show that for a given number of TCP flows K, an increase of N causes an increase in the PER, when static resourcereservations (here: according to peak bit rate) are used. Dynamic bandwidth allocation (Fig. 3c) deepens this trend. Note that, in successive graphs, ordinates differ by an order of magnitude.

C. Preserving overall throughput of video streams

Table 1 shows that in an unloaded network ($K = 0$) PERs equal zero. Because video traffic is rate-limited, if $K = 0$, overall throughput of the HD video (Table 2) determines the required, sumarized throughput of all streams. If $K > 0$, in the case of the best effort service, throughput of the video traffic is, generally, smaller (and, sometimes, much smaller) than is required by real-time transmission. In the worst case (one HD video stream competes for bandwidth with 10 TCP flows, $K = 1, N = 10$), the HD video transmission achieved only 54 percent of the required throughput.

The s4 scenario allows the same throughput to be achieved (with an accuracy of 1 Mbps) for HD video traffic, compared to what is required. Only in the worst case ($N = 1$,$K = 9$ or $K = 10$), the throughput of the HD video stream achieve 98 percent of the required value. It still allowed for $PER = 0$.

For comparison, if $N = 1$ and $K = 10$, the throughput of the video stream achieves 81 percent of the required value when s2 scenario was used and 95 percent when s3 scenario was used. If $N = 1$ and $K = 9$, throughputs observed for s2, s3, and s4 scenarios are comparable (97 to 98 percent of the required value). However, if $K > 0$, the use of static reservations (s2 and s3) do not allowed for $PER = 0$.

D. Limiting overall throughput of TCP flows and preserving link utilization

The high aggressiveness of the TCP results in a higher throughput for TCP flows that compete in a shared link with HD video streams (Table 2) transmitted with the use of best effort service. Video transmissions pay for the larger TCP throughput with unacceptable RTP packet loss, while the percentage utilization of the shared link is at a maximum.

Static reservations that are based on RSVP signalling (s2 and s3 scenarios) reduce excessive TCP throughput. This reduction is larger (and sometimes much larger) if overestimated reservations, based on peak bit rate (s3 scenario), were applied for QoS protection of HD video transmission. However, the percentage utilization of the shared link is smaller than what is observed when the best effort service was used.

Dynamic reservations that are based on TFD signalling (s4 scenario) have the ability to deal with the trade-off between the need for limited throughput of TCP flows and an as large as possible utilization of the shared link. Applying dynamic reservations allow TFD-capable networks to have the smallest reduction of the TCP throughput (when compared to the best effort service) of all tested methods of QoS assurance. In the case of the s4 scenario, both the overall TCP throughputs and the overall video throughputs were greater or the same as those obtained for RSVP-based reservations. It results in the largest link utilization from the applied methods of QoS assurance, comparable with the one obtained for the best effort.

VI. Conclusion

This paper presents a performance evaluation of HD video transmissions that were QoS-protected with the use of TFD-capable routers, able to process detailed knowledge about transmitted traffic (conveyed in the Traffic Flow Description option of the IP protocol) and to use it for dynamic resource allocation. The analysis was illustrated with the example of N HD video streams, $N = 1, 2, ..., 10$, transmitted through a gigabit link that was shared with K TCP flows, $K = 0, 1, ..., 10$. Results were compared with results obtained from the best effort service and two static reservations (amounting to 150% of target bit rate and the peak bit rate) based on signalling delivered by the RSVP.

The performance evaluation shows that the use of TFD-capable QoS assurance significantly reduces the packet error rate of transmitted HD video. Packet error rate was an order of magnitude smaller than what was measured for RSVP-based reservations made according to the peak bit rate. The TFD-cabable, dynamic resource reservation have the ability to better, than the static one, preserve overall throughput of transmitted video streams, and to limit overall throughput of TCP flows to a reasonable range. Thus, despite the use of QoS assurance, utilisation of shared link is close to what was achieved when best effort service was used.

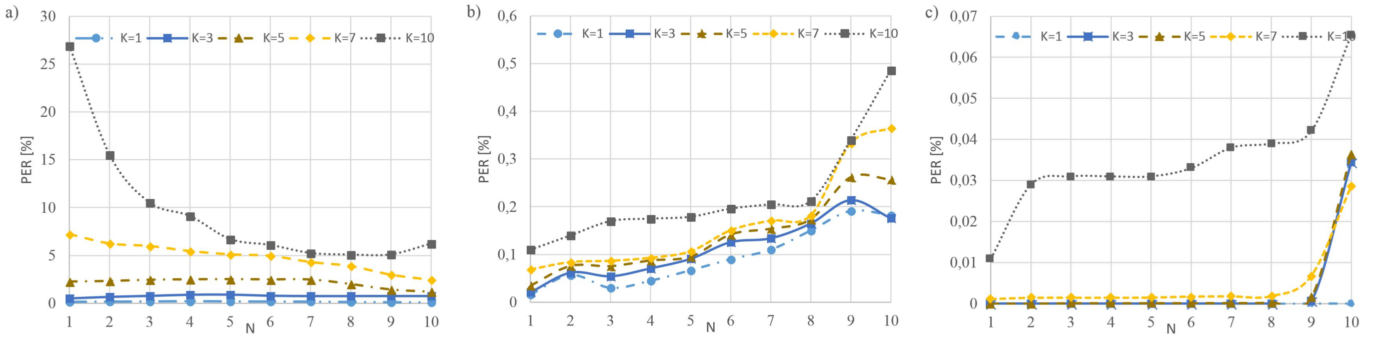

Fig. 3. Chosen packet error rates observed for: a) s1 scenario, b) s3 scenario, c) s4 scenario

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