An Equivalent Circuit Rate-Based Study of Next-Generation Optical Access Architectures

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ABSTRACT

In this paper we report the results of our first attempt to quantify a bandwidth requirement for next-generation optical access architectures based on passive optical network (PON) technology. It has been well known that shared architectures can enjoy statistical multiplexing gain, but the amount of the gain is highly dependent upon the nature of traffic, network architectures, and so on. To take into account the interactive nature of actual traffic (e.g., TCP flow control) and the performances perceived by end-users (e.g., delay in web browsing) in quantification of the statistical multiplexing gain, we use the equivalent circuit rate (ECR) as an analysis framework and a behavioral model for web browsing as a user traffic model in the simulation, which is implemented using OMNeT++ with INET framework providing models for the complete Internet protocol stack. The simulation results for the abstract models of various PON-based architectures have shown that, among shared architectures, a hybrid time division multiplexing (TDM)/wavelength division multiplexing (WDM)-PON with a feeder rate several times higher than a distribution rate can provide the same user-perceived performance as a dedicated network architecture with the same line rate as the distribution rate — i.e., point-to-point network or a pure WDM-PON — for a reasonable range of input load.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Network Communications and Network Topology

General Terms

Performance, Design, Economics, Experimentation

Keywords

Equivalent Circuit Rate, Next-Generation Optical Access, Passive Optical Networks, HTTP Traffic Model, OMNeT++

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1. INTRODUCTION

Optical access has been considered an ideal solution to the problem of upgrading the current bottlenecked access to the one capable of delivering future broadband integrated services due to the huge capacity of optical fiber. Because optical fiber has been used in backbone networks, wide area networks (WANs), and metropolitan area networks (MANs), and are also being introduced in local area networks (LANs) with the advent of optical Ethernet, the implementation of the optical access will be the last step to future all-optical-network revolution [11].

One of the major questions at hand is not whether we should implement optical access or not, but when and how we should. The choice of a network architecture in this regard, therefore, becomes a critical concern within the optical networking community. In this paper we tackle the issue of quantifying the bandwidth requirement for valid and objective assessment of candidate architectures for next-generation optical access with the help of a new analysis framework and OMNeT++ [17] with INET [6] simulation package.

Traditional point-to-point optical network architectures are expensive for access configurations: Besides fiber deployment costs, they need maintenance for the outside plant including active systems. These systems consist of many electrical-to-optical (E/O) and optical-to-electrical (O/E) components prone to failure, which prevent their large-scale deployment. To address these issues, time division multiplexing-passive optical networks (TDM-PONs) have been developed, which are currently being deployed in the field by network service providers in several places around the world, mostly in Japan, Korea, and the United States [14]. In a few years, once TDM-PONs are deployed in a large scale, upgrading these optical access networks will be a challenge when user demand outgrows the existing access network capacities. Because TDM-PONs use only one wavelength for each direction of downstream and upstream communication, whose capacities are shared by all subscribers, the average bandwidth per user is limited to a few tens of Mb/s [7]. Wavelength division multiplexing (WDM) technology can be used to extend the capacity of optical access without drastically changing the fiber infrastructure [10]. However, integrating WDM and TDM to ensure the flexibility of the optical access while maintaining total costs at a reasonable level still requires further investigation. For the review of next-generation PONs and the issues in using TDM and WDM in access, readers are referred to [1, 8, 9, 5, 4].

In selecting a network architecture for the next-generation

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optical access, one fundamental issue is a bandwidth requirement: *How much bandwidth will be enough to meet user demands for future services and applications?*. Especially, when we are talking about "10 Gb/s access" [16], it's not clear whether this means 10 Gb/s per user in a non-contentious way or not. If "10 Gb/s access" means 10 Gb/s capacity per user in a non-contentious way, only a dedicated network architecture with a line rate of 10 Gb/s, like point-to-point or pure WDM-PONs, can meet this requirement. Otherwise, shared architectures like 10 Gb/s TDM-PONs and hybrid TDM/WDM-PONs can be considered as solutions as well.

In fact, specifying the user bandwidth requirement is a very complicated issue. For instance, 10 Gb/s line rate in the access is a necessary but not sufficient condition because some degree of contention can be assumed at various points in the network from access to backbone. In this paper we will focus on the access side only and leave the issues with metro and backbone for later work. Then, the original question becomes "*What does 10 Gb/s means at the user side?*". To answer this question, certainly we need a quantifiable and measurable definition of "10 Gb/s". The answer to this question will eventually decide whether we can use shared network architectures for the next-generation optical access, which can provide the advantage of the economy of scale through integration and sharing network resources like "Cloud Computing" [2].

Considering the dynamic and interactive nature of transmission control protocol (TCP) and the highly bursty characteristic of future video traffic [3], by the way, one can expect that in case of a dedicated network architecture, it is practically impossible for user traffic to consume the whole bandwidth assigned and that this eventually leads into a significant waste of valuable resources including transceivers and power they use. Here we propose a quantitative analysis framework based on the notion of equivalent circuit rate (ECR) [15], which can take into account the said interactive nature of actual traffic and user-perceived performances, and carry out a comparison study for candidate architectures for the next-generation optical access based on the proposed framework.

The outline of the paper is as follows: Section II describes a proposed analysis framework based on the ECR. Section III describes a simulation setup for a comparison study with models for candidate architectures and a user traffic. Section IV presents and discusses initial results from this comparison study and Section V summarizes our work in this paper and provides directions for further research.

2. QUANTITATIVE ANALYSIS FRAMEWORK

It has been well known that shared architectures can enjoy statistical multiplexing gain, although the amount of the gain is dependent upon the nature of traffic, network architectures, and so on [13]: A classical queueing theory to various simulation results indicate that there is a statistical multiplexing gain over most of random traffic, but few of them take into account the interactive nature of actual traffic (e.g., TCP flow control) and the performances perceived by end-users (e.g., delay in web browsing). Because of these, the practicality of statistical multiplexing gain and thereby shared architectures become questionable, especially for future optical access. It is mainly in this background where many in the optical access community believe that we should go for a dedicated architecture like point-to-point or WDM-PONs in the future from the current shared architecture of TDM-PONs.

To take into account both the interactive nature of traffic and user-perceived performances in quantifying the performances of various optical access architectures, therefore, we propose a quantitative analysis framework based on the notion of ECR as illustrated in Fig. 1.

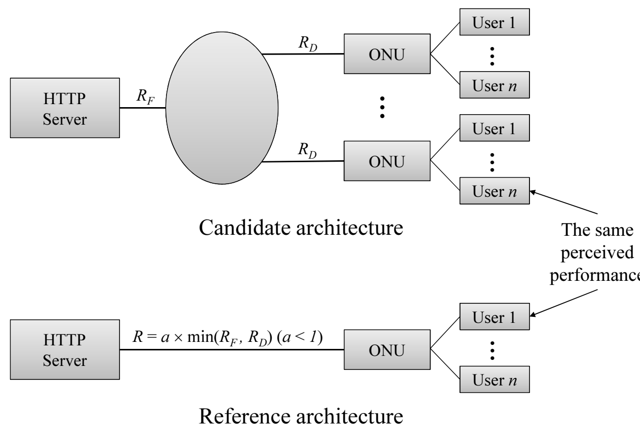

Figure 1: Quantitative analysis framework based on ECR where R_F and R_D are feeder and distribution rates of a candidate architecture and R is a line rate of a reference architecture.

Note that the ECR was originally proposed for a quantitative comparison of hybrid fiber coaxial (HFC) cable-based shared access network and digital subscriber line (DSL)-based dedicated access network architectures. This ECR-based framework, however, can be easily extended for a quantitative comparison of various PON-based architectures as shown in Fig. 1. In this framework we will compare the user-perceived performance of a candidate network architecture to that of a reference network architecture which is dedicated, point-to-point. In case of a shared architecture, because of contention for a feeder capacity (i.e., R_F) among multiple optical network units (ONUs) and for a distribution capacity (i.e., R_D) among multiple users connected to the same ONU, we can expect that their share of capacity cannot be greater than the minimum of feeder and line rates. Therefore the user-perceived performance would be similar to that of a reference architecture with a line rate less than the minimum of the feeder and the distribution rates of the candidate architecture.

Fig. 2 describes how to calculate the ECR of a candidate architecture where we use a web page delay as a measure for the user-perceived performance as in [15]. To calculate the ECR of a candidate architecture with given feeder (R_F) and distribution rates (R_D), first we need to obtain web page delays from the simulation with a reference architecture for line rates between 0 and $\min(R_F, R_D)$. Then, based on the simulation results for web page delay, we build a function (or a table) $f(R) = D_w$ where D_w denotes web page delay. Finally, we obtain a web page delay from the simulation with a candidate architecture and calculate the ECR by solving the equation $f(ECR) = D_w$. In this way, we can calculate the ECR of the candidate architecture which provides the

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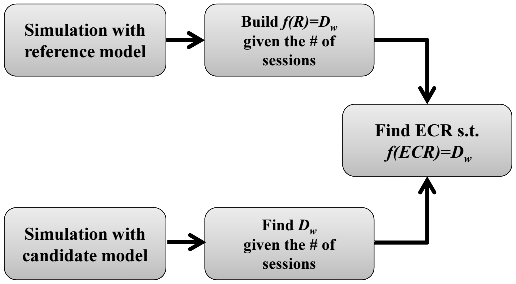

Figure 2: ECR calculation procedure where D_W denotes web page delay.

same user-perceived performances as the reference architecture with the access rate of $R = ECR$.

3. SIMULATION SETUP

To capture the interaction of many traffic flows through TCP and a candidate network architecture, we implemented a simulation model based on OMNeT++ [17] with INET framework [6] which provides a complete TCP/IP protocol stack.

Fig. 3 (a) and (b) show the block diagrams of typical TDM-PON and hybrid TDM/WDM-PON, respectively. As

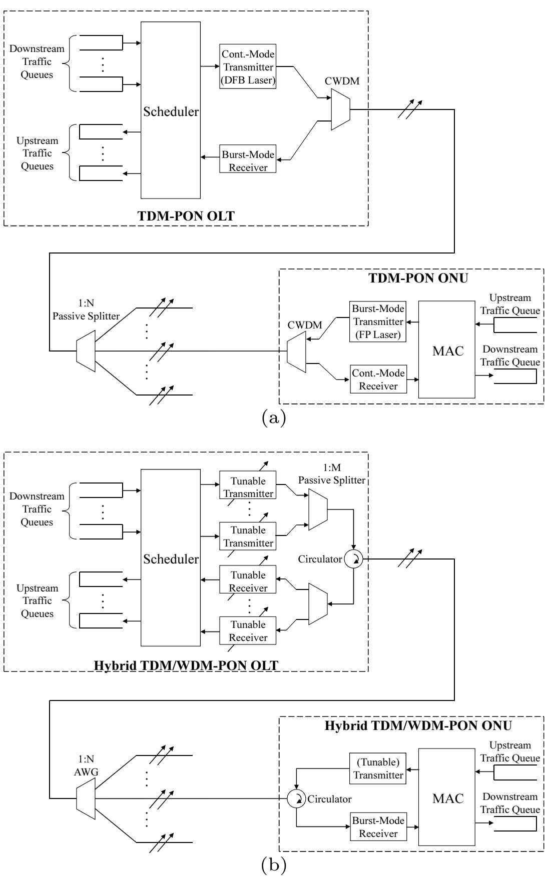

Figure 3: Block diagrams of (a) TDM-PON and (b) hybrid TDM/WDM-PON.

you can see from the block diagrams, there are many components (e.g., "scheduler" and "MAC") whose actual implementations directly affect the system performances. Because our major focus in this paper is to carry out a high-level comparison of network architectures for the next-generation optical access rather than that of specific implementations, we intentionally limited ourselves to abstract models based on IP routers with different setups for their line rates to minimally capture the distinctive characteristics of target architectures, while we put more focus on implementing a realistic HTTP traffic model and the ECR framework.

Fig. 4 (a) and (b) show models for end-to-end communications in a dedicated (i.e., point-to-point) and a shared access architectures, respectively, based on the said abstraction. Note that TDM-PONs can be modeled by setting R_F=R_D and hybrid TDM/WDM-PONs by setting R_F to integer multiples of R_D in Fig. 4 (b). In actual simulation, we set R_D and R_B to 10 Mb/s[1] and 1 Tb/s, respectively, and replaced the access and backbone blocks with high capacity IP routers which multiplex and demultiplex traffic flows between the HTTP server and the access network. Also, RTT was fixed to 10 ms throughout the simulation.

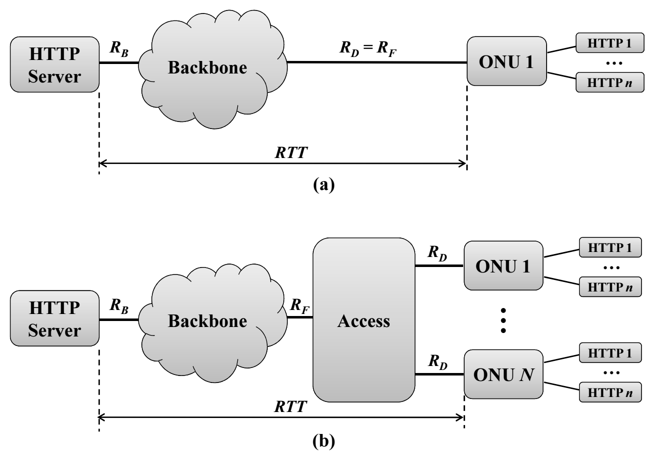

Figure 4: Models for end-to-end communications in (a) dedicated and (b) shared access architectures where R_D, R_F, and R_B denote distribution, feeder, and backbone rates and RTT end-to-end round-trip time.

For a user traffic model, we adopted a behavioral model for user(s) web browsing shown in Fig. 5, which is based on the model in [12] and adapted for traffic generation at the client side above TCP layer. For simplicity, we assume that there is no caching and pipelining in a browser. The parameter values used for simulation are summarized in Table 1. Note that with RTT=10ms, the average web page (session) delay and session period (including *reading time*) are given by 3.18 sec and 42.88 sec, respectively. Also, the average load (i.e., the number of bytes divided by the session period) is given

[1]We scaled it down by 1000 compared to the original target rate of 10 Gb/s for the next-generation optical access. This scaling down could save simulation run time significantly, of course, but we also did it because filling up the whole 10 Gb/s lines with HTTP traffic only does not make much sense. Certainly, we need a more realistic traffic scenario consisting of high-bandwidth multimedia traffic (e.g., HD-TV) as well as HTTP traffic for true 10 Gb/s-rate simulation.

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by 1750.07 B/sec (about 14 kb/s), which means that we need about 714 sessions to fully load the 10 Mb/s line.[2]

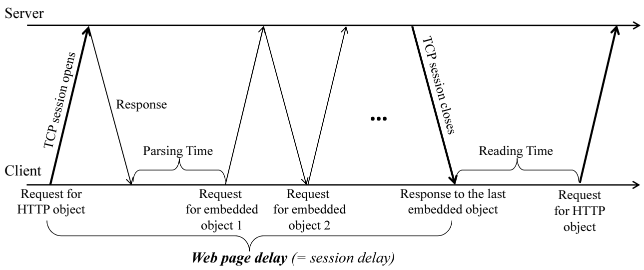

Figure 5: HTTP traffic model.

4. INITIAL RESULTS AND DISCUSSIONS

Figs. 6, 7, and 8 show web page delays for ECR reference (i.e., point-to-point), TDM-PON and hybrid TDM/WDM-PON architectures, respectively. Note that in Fig. 6, the web page delay is shown as a function of the access rate (R_D=R_F), while in Figs. 7 and 8, it is shown as a function of the number of sessions per user (n).

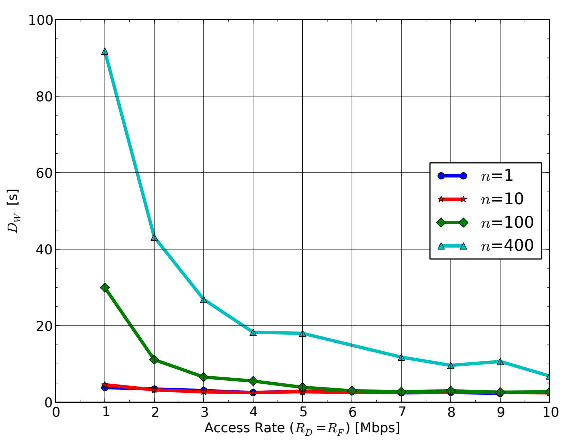

Figure 6: Web page delay for ECR reference model with RTT=10 ms.

Based on the results shown in Figs. 6, 7, and 8, and the ECR calculation procedures shown in Fig. 2, we obtained ECRs for hybrid PONs as shown in Fig. 9 where TDM-PON is a special case of hybrid PON with R_F=R_D. Note that the ECR curves shown in Fig. 9 are least-square-fitted exponential functions; the ECRs calculated from actual data are shown as points. As expected, higher feeder rates provide ECR of equal to or greater than 10 Mb/s for a reasonable range of n. For example, when R_F=4R_D, hybrid PON can provide the same user-perceived performance as a dedicated architecture until the number of web sessions reaches 20. On the other hand, there is no range of input load for TDM-PON (i.e., R_F=R_D) where users can experience the same performance as in a dedicated architecture. The benefits of

[2]These are rough estimations only. In reality, due to the interactive nature of TCP flow control, the actual numbers would be different.

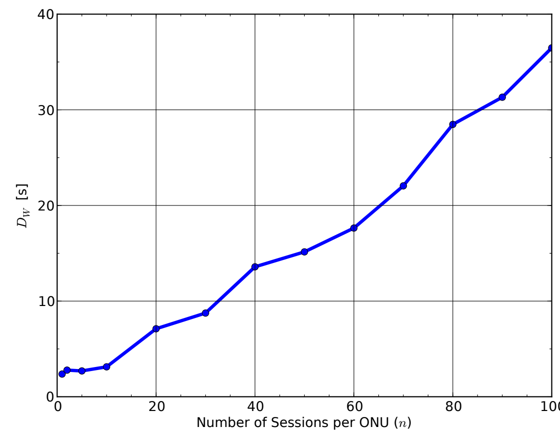

Figure 7: Web page delay for TDM-PON with N=16 and RTT=10 ms.

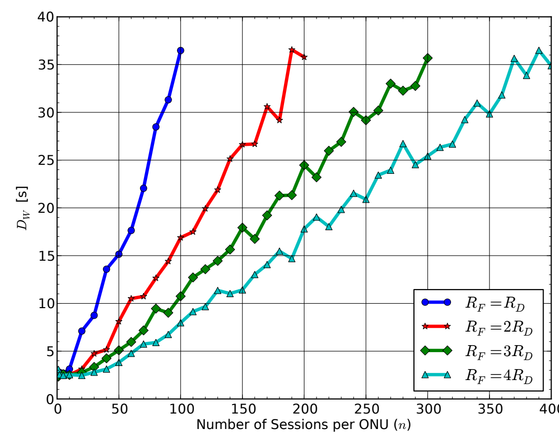

Figure 8: Web page delay for hybrid PON with N=16 and RTT=10 ms.

hybrid PON over TDM-PON is more clearly seen from Fig. 10 which shows the minimum ratio of R_F/R_D to achieve the ECR of 10 Mb/s.

Considering that the lines in Fig. 10 are from the fitted curves and that actual ECRs are defined only for discrete values of n, again we found that TDM-PON can never provide the same user-perceived performance as a dedicated architecture. In case of hybrid PON, on the other hand, we found that even with R_F=2R_D it can provide the same performance as a dedicated architecture for up to four web sessions per ONU.

From the initial results presented in this section, we can derive the following points:

- A dedicated architecture with 10 Mb/s line rate can provide the ECR of 10 Mb/s all the time (by definition of ECR) as far as there is no bottleneck in the network side.
- With a dedicated architecture, however, we cannot enjoy any statistical multiplexing gain (i.e., sharing of

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Table 1: Parameter values for HTTP traffic model (from [12])

Parameters/Measurements	Best Fit (Parameters)
HTML Object Size [Byte] / Mean=11872, SD=38036, Max=2M	Truncated lognormal (μ=7.90272, σ=1.7643, max=2MB)
Embedded Object Size [Byte] / Mean =12460, SD=116050, Max=6M	Truncated lognormal (μ=7.51384, σ=2.17454, max=6MB)
Number of Embedded Objects / Mean=5.07, Max=300	Gamma (κ=0.141385, θ=40.3257)
Parsing Time [sec] / Mean=3.12, SD=14.21, Max=300	Truncated lognormal (μ=-1.24892, σ=2.08427, max=300sec)
Reading Time [sec] / Mean=39.70, SD=324.92, Max=10000	Lognormal (μ=-0.495204, σ=2.7731)
Request Size [Byte] / Mean=318.59, SD=179.46	Uniform (a=0, b=700)

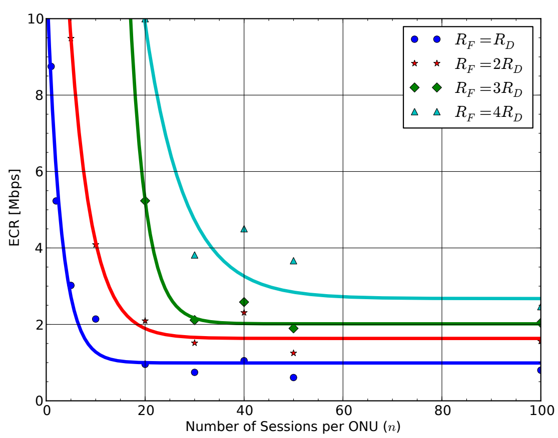

Figure 9: ECR for hybrid PON with N=16 and RTT=10 ms.

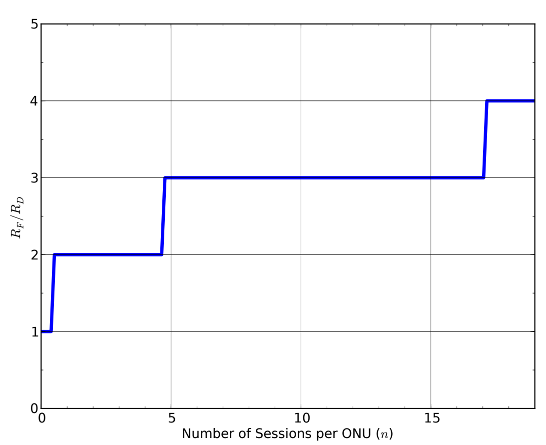

Figure 10: Minimum ratio of R_F/R_D to achieve the ECR of 10 Mb/s in hybrid PON.

resources) other than some fiber infrastructure in case of WDM-PON.

- Shared architectures with access rate of 10 Mb/s may or may not provide the ECR of 10 Mb/s depending on the input load; we need to increase either the whole line rates (i.e., R_F and R_D) in TDM-PON or the number of tunable transceivers (i.e., R_F) in hybrid TDM/WDM-PON.

5. SUMMARY

We have proposed a quantitative analysis framework for the next-generation optical access based on the notion of ECR extended for various optical network architectures and carried out a comparison study based on the proposed framework. This was our first attempt to quantify the user bandwidth requirement in the next-generation optical access. Our suggested answer to the question of "What does 10 Gb/s means at the user side?" is that it means each user enjoy the same perceived performance as in a dedicated network architecture with a line rate of 10 Gb/s. Note that this definition of user bandwidth requirement (i.e., ECR of 10 Gb/s in this case) is not specific to a network architecture and therefore does not exclude a possible use of shared architectures for the next-generation optical access, which are much more favorable in terms of power and economic efficiency due to their sharing of network resources.

Initial results from the simulation with a target rate of 10 Mb/s (scaled down by 1000) and web traffic only suggest that shared architectures need either line rates higher than 10 Mb/s (in case of TDM-PON) or multiple tunable transceivers (in case of hybrid TDM/WDM-PON) to achieve the ECR of 10 Mb/s.

Note that all the models described in this paper are available at "http://github.com/kyeongsoo/inet-hnrl" as it has been forked form the INET framework. Because of the use of abstract models for network architectures, we can consider the performance results in this paper as rough upper bounds for those of specific PON models taking into account implementation details, which are under active development now.[3] Also note that in its current form, the results are limited to web traffic only and that we are currently working toward the inclusion of future video traffic (e.g., H.264/AVC [3]) in the proposed analysis framework as well.

6. ACKNOWLEDGMENTS

[3]In fact, they are already part of the said github repository, but not fully integrated into the INET framework yet.

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