A Research Framework for the Clean-Slate Design of Next-Generation Optical Access

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Abstract A comprehensive research framework for a comparative analysis of candidate network architectures and protocols in the clean-slate design of next-generation optical access is proposed. The proposed research framework consists of a comparative analysis framework based on multivariate non-inferiority testing and a notion of equivalent circuit rate taking into account user-perceived performances and a virtual test bed providing a complete experimental platform for the comparative analysis. The capability of the research framework is demonstrated through numerical results from the study of the elasticity of hybrid time division multiplexing/wavelength division multiplexing–passive optical network based on tunable transceivers.

Keywords next-generation optical access, comparative analysis, virtual test bed, equivalent circuit rate, statistical hypothesis testing, non-inferiority testing, quality of experience

1. Introduction

While investigating the issues of quality of experience (QoE), elasticity, and energy efficiency in next-generation optical access (NGOA) as part of research programs since 2009 [1–3] with a major focus on the solutions beyond 10-Gbit/s Ethernet passive optical network (10G-EPON) and 10-gigabit-capable passive optical network (XG-PON) (e.g., NG-PON2 [4] by ITU-T), it has been noted that the progress in the clean-slate design of NGOA is impeded by the absence of a comprehensive research framework for a comparative analysis of candidate network architectures and protocols. In fact, many NGOA network architectures that have been proposed by both academia and industry are now under extensive study (e.g., [5–8]). Unfortunately, most of the existing works lack a systematic comparison of candidate architectures under realistic operating environments; they are based on the comparison of network-level performances (e.g., packet delay and throughput), reaches, splitting ratios, and energy consumptions under static or limited statistical traffic configurations without taking into account the actual performances perceived by end-users that reflect the impact of higher-layer protocols including transmission control protocol (TCP) flow and congestion control.

Elasticity means the ability to manage overall performances to a certain level by fast provisioning of network resources based on user demands.

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Because of the complexity of protocols and the interactive nature of traffic involved in the study of network architectures, researchers now heavily depend on experiments with simulation models or test beds implementing proposed architectures and relevant protocols, rather than traditional mathematical analyses under simplifying assumptions. In this regard, a research framework for the comparative analysis of NGOA architectures and protocols should specify how to generate traffic and measure performances during the experiment, together with a systematic comparison of the measured performances from the experiments. Note that, due to the shift toward experiments, comparison procedures should be able to take into account the statistical variability in measured data from the experiments.

In this article, a new research framework for the clean-slate design of NGOA architectures and protocols is proposed. The proposed research framework consists of two major components, i.e., a comparative analysis framework and a virtual test bed for experiments.

The comparative analysis framework is based on a multivariate non-inferiority testing procedure [9, 10] and a notion of equivalent circuit rate (ECR) [11]. In this framework, user-perceived performances of representative services—including web browsing (i.e., hypertext transfer protocol [HTTP], file downloading (i.e., file transfer protocol [FTP]), and streaming video (i.e., H.264/advanced video coding [AVC] with user datagram protocol [UDP])—are compared in an integrated way using statistical hypothesis testing procedures.

The virtual test bed is basically simulation models of the proposed architectures and protocols. Unlike many existing works in the area of optical access that mainly focus on the issues up to the data link layer (e.g., [12–15]), the virtual test bed provides a complete experimental environment with session-level traffic generation (based on user behaviors) and performance gathering (as measures for user-perceived performances), as well as models for the whole network protocol stack (including TCP/internet protocol [IP]).

The rest of the article is organized as follows: Section 2 describes the comparative analysis framework based on the multivariate non-inferiority testing and the ECR. Section 3 provides an overview of the current implementation of the virtual test bed and discusses plans and strategies for its improvement in the next version. Section 4 presents results from the study of the elasticity of hybrid time division multiplexing (TDM)/wavelength division multiplexing (WDM)–passive optical network (PON) to demonstrate the capability of the proposed research framework. Section 5 concludes the discussions in this article.

2. A Comparative Analysis Framework

Figure 1 illustrates an example of comparison between two delay curves at a certain value of load (i.e., $x$), which is typical in the performance analysis of a new proposed system with respect to an existing one. At first glance, the comparison seems straightforward; one can say from the curves that system B provides a lower delay than system A at load $x$. If the statistical variability in measured data (i.e., the overlapped confidence intervals in the enlarged part) is taken into account, however, the comparison is no longer straightforward, and a statistical approach is needed in this regard.

Note that most of the works in networking area lack a statistical approach in the performance comparison and just provide observations on certain trends. For example, “system B provides a better delay performance than system A when the load is greater than $x$” is a typical observation for Figure 1, and the exact value of $x$ is not that critical.
As will be discussed shortly, however, the strict comparison of performances at a certain input value is quite critical to comparison frameworks like the ECR. Also, considering other performance measures (e.g., throughput) as well as delay curves for multiple services (e.g., HTTP and FTP) altogether, the performance comparison between the systems becomes even more complicated.

As the clean-slate design of NGOA is still at an early stage, it is therefore critical to establish a new framework for comparing candidate network architectures and protocols that meets the following requirements:

- a comparison procedure should take into account the statistical variability in measured data resulting from the experiments;
- multiple performance measures should be compared together in an integrated way; and
- measures for the comparison should be user oriented; in other words, they should reflect the QoE rather than the quality of service (QoS).

To meet these requirements, work on a new comparative analysis framework based on the non-inferiority testing for the comparison procedure and the ECR for the quantification of the resulting performance is underway. Non-inferiority testing is a one-sided variant of the equivalence testing that is frequently used in medicine and biology for the establishment of the equivalence (often called bioequivalence) between two different clinical trials or drugs [10, 16, 17]. The ECR, on the other hand, was originally proposed for the quantification of the bandwidth of hybrid fiber coaxial (HFC) cable-based shared access network with respect to that of the digital subscriber line (DSL)-based dedicated access network in terms of webpage delay as a measure for user-perceived performances [11]. The ECR framework has been extended for a quantitative comparison of optical access architectures in [1, 2].

Combining these two frameworks, the proposed comparative analysis framework can meet the aforementioned requirements. The non-inferiority testing procedure is based on statistical hypothesis testing and, as such, takes into account the statistical variability
inherent in measurements as well as experiments. To compare multiple performance measures in an integrated way, the non-inferiority testing is extended by the intersection-union testing (IUT) as described in [16]. The third requirement is met by the ECR, which enables the quantification of the relative capacity of a candidate system with respect to a reference one based on user-perceived performances at the application level.

Figure 2 shows the comparative analysis framework based on the ECR for the investigation of NGOA architectures and protocols: \( R_B \) and \( R_U \) denote the backbone and the user network interface (UNI) rates for both the reference and the candidate architectures. On the other hand, \( R_F \) and \( R_D \) denote the feeder and the distribution rates of the candidate architecture, and \( R \) denotes the line rate connecting the optical line terminal (OLT) and the optical network unit (ONU) of the reference architecture. In this framework, the user-perceived performances of both the candidate and the reference architectures are compared for fixed values of \( R_B \), \( R_U \) (common for both the architectures) \( R_F \), and \( R_D \) (for the candidate architecture) and a range of values of \( R \) (for the reference architecture); the value of \( R \) (i.e., ECR) for the reference architecture, which gives user-perceived performances statistically equivalent to those of the candidate architecture, is calculated.

In case of a shared architecture, for instance, because of contention for a feeder capacity among multiple ONUs and for a distribution capacity among multiple users connected to the same ONU, each user’s share of capacity cannot be greater than the minimum of the feeder and the distribution capacities. Therefore, the user-perceived performance would be similar to that of the reference architecture with the line rate equal to or less than the minimum of the feeder and the distribution rates of the shared architecture.

Note that the original ECR framework [11] is based on a single performance measure of webpage delay and does not provide any systematic comparison procedure taking into account the statistical variability in measured data. Figure 3 shows the new procedure for calculating the ECR based on multivariate non-inferiority testing (i.e., non-inferiority testing extended by the IUT), where \( N_M \) and \( N_R \) denote the number of performance measures adopted and the number of values for \( R \) (i.e., \( R_i \)'s) used for comparison, respectively.

First, measures of the user-perceived performances for representative applications/services (i.e., \( M_1, \ldots, M_{N_M} \)—e.g., webpage delay defined as the average time taken

![Figure 2. Comparative analysis framework based on the ECR.](image-url)
Figure 3. ECR calculation procedure based on non-inferiority testing: (a) multivariate non-inferiority testing based on IUT and (b) ECR calculation.

(continued)

to download an entire webpage [11] and the fraction of decodable frames per group of pictures (GoP) (also called “decodable frame rate” [DFR]) for streaming video [18]—are to be obtained for the reference architecture at the line rates of $R_1, \ldots, R_{N_R}$, where $R_1 = \min(R_F, R_D)$, $R_{N_R} > 0$, and $R_i > R_j$ for $i < j$.

Second, using the procedure shown in Figure 3, a value for the line rate of the reference architecture for which the measures of the candidate architecture are statistically non-inferior to those of the reference architecture is calculated. The null and the

$^2$Note that the resolution of the ECR depends on the number of $R_i$s (i.e., $N_R$) and proper choice of their values.
alternative hypotheses of the non-inferiority testing for measure $M_i$ (e.g., webpage delay) are given by

$$
\begin{align*}
H_0 : \mu_{i,C} - \mu_{i,R} & \geq \delta_i \\
H_1 : \mu_{i,C} - \mu_{i,R} & < \delta_i
\end{align*}
$$

(1)

where $\mu_{i,C}$ and $\mu_{i,R}$ denote population means of $M_i$ for the candidate and reference architectures, respectively, and $\delta_i$ represents the tolerance for the measure $M_i$. The null hypothesis ($H_0$) is rejected if the limit of one-sided confidence interval for the difference (i.e., $\mu_{i,C} - \mu_{i,R}$) is less than the tolerance [19]. This means that the candidate architecture is “at least as good as” the reference architecture for the given measure $M_i$. Note that
for each measure $M_i$, an appropriate tolerance value ($\delta_i$) should be determined, and, if needed, the hypotheses should be changed accordingly. For example, the hypotheses for the DFR of streaming video—the higher, the better, in this case—need to be changed as follows:

$$
\begin{align*}
H_0 : \mu_{i,C} - \mu_{i,R} &\leq -\delta_i \\
H_1 : \mu_{i,C} - \mu_{i,R} &> -\delta_i
\end{align*}
$$

(2)

3. A Virtual Test Bed for Experiments

To support the new comparative analysis framework described in Section 2, a flexible, yet computationally powerful, experimental platform is needed; to carry out the statistical hypothesis testing in the proposed ECR calculation procedure, a sample of performance measures should be big enough to compute a reliable test statistic. In the case of simulation experiments, this means that a simulation has to be repeated many times with a different random number seed per run, which is quite challenging for large-scale simulations.

The experimental platform also should be able to capture the interaction of many traffic flows through a complete protocol stack, which are generated either by actual users or, as a practical alternative, based on user behavior models. A real, physical test bed in this regard is hardly a viable option, considering a long cycle of design and performance evaluation of new architectures and protocols, at least at the stage of the clean-slate design.

In this regard, it is decided to implement a virtual test bed composed of detailed simulation models based on OMNeT++ [20] and the INET framework [21], which provide models for end-user applications as well as a complete TCP/IP protocol stack.\(^3\) Note that simulation studies in the optical networking area usually focus on the issues at the physical and/or the data link layer only but neglect the issues at higher layers due to the limit in computing power. The recent introduction of high-performance computing (HPC) clusters and cloud computing [22], however, brings enormous computing power at a much lower cost and, in case of cloud computing, on-demand basis; this enables researchers to carry out a series of large-scale network simulations in a realistic environment, which was neither practical nor economically feasible in the past. Specifically, Amazon elastic compute cloud (Amazon EC2) [23] is being used as a running platform for the virtual test bed, while programs are being developed at a local HPC cluster for ease of testing and debugging processes.

Figure 4 shows the overview of the virtual test bed, where major building blocks are identified in addition to the system under test between the service node interface (SNI) and the UNI. For the reference architecture model, the OLT and the ONU are implemented using a general IP router and an Ethernet switch. For the candidate architectures, the hybrid TDM/WDM-PON under the Stanford University aCCESS-Hybrid PON (SUCCESS-HPON) architecture [15] has been already implemented, and the implementation of 10G-EPON is currently underway.

Figure 5 shows a multi-level approach to traffic modeling and generation in the virtual test bed; as indicated by the dotted line in the figure, a user-level behavioral model governing underlying applications/services is still missing in the current implementation, while session-level and packet-level models have already been implemented for HTTP,

\(^3\)The implemented simulation models are available at http://github.com/kyeongsoo/inet-hnrl.
FTP, and UDP streaming video [24]. The model proposed in [25] was adapted for HTTP traffic generation at the client side above the TCP layer and without caching and pipelining in a browser, while the FTP model from [26] was used without any modification. For both traffic types, the virtual test bed provides a capability of measuring session-level delay, throughput, and transfer rate as an indirect measure of user-perceived performances.

In addition to HTTP and FTP traffic, a model for high-rate, HDTV-quality streaming video traffic for the virtual test bed is also implemented, which is considered one of the killer applications for NGOA. The implemented traffic model can generate frames based...
on trace files from the Arizona State University (ASU) video trace library [27]. As a measure of user-perceived quality of video stream, the DFR is adopted, which is defined as the ratio of successfully decoded frames at a receiver to the total number of frames sent by a video source [18]. The larger the value of the DFR, the better the video quality perceived by the end-user is. For details of the implemented traffic models, readers are referred to [24].

Figure 6 shows a model for an end-user node that is connected to the ONU through UNI. Currently, the number of traffic sessions (i.e., \( n_h, n_f, \) and \( n_v \)) is static and configured at the beginning of a simulation through an input file. Once a user-level behavior model is implemented, however, the number of traffic sessions will be dynamically controlled by it during the simulation.

### 3.1. Issues and Challenges

Here are the lessons from the work reported in this article. Because it is necessary to run multiple simulations for given parameters in order to compute a test statistic for the ECR calculation, each simulation was repeated five times with different random number seeds. Each simulation ran for 3 hr in simulation time (much longer in real time), and the data were gathered after a warm-up period of 20 min; the warm-up period should be long enough to reduce the transient effects from the PON ranging procedure and start-up delays introduced by streaming video encoding/decoding processes as well as networking protocols like TCP.\(^4\) The total number of simulation runs for the initial work is more than 1000 (i.e., 780 and 250 for the reference and the shared architectures, respectively), and it took several months to finish all simulations with a Linux HPC cluster with 22 computing nodes, each with 8-GB memory and an 8-core Intel Xeon CPU running at 2 GHz.

As discussed before, cloud computing could be a solution in this regard; one can run 1000+ simulations simultaneously with the equal number of virtual computers (or

\(^4\)The warm-up period of 20 min was indirectly determined by investigating the total number of scheduled events in the future-event list; it was observed that after 20 min, the number of scheduled events throughout the system goes into a steady state for all the simulations considered.
cores) in principle. To reduce the run time of each individual simulation, however, another approach is needed on top of cloud computing: parallelization. Fortunately the OMNeT++ supports parallel simulation through message passing interface (MPI) library [28], and the implemented models are currently being extended for parallel simulation. Once the virtual test bed is ready for parallel simulation, the number of virtual computers can be increased to speed up run times (e.g., 2,000 for 1,000 simulations).

As for the user-level behavioral model currently missing, a demographic and behavioral user profile will be built by focusing on groups for initial exploration and surveying large-scale data collection. Note that because there is no NGOA network deployed now, the use of demographic and behavioral profile obtained from the survey for the architectural study is the only practical option. Then the user-level behavioral model governing underlying application-level traffic models will be built based on the developed profile, which can capture the difference between business and residential users and temporal aspects of end-user behaviors [3].

4. Numerical Examples: Elasticity of Hybrid TDM/WDM-PON with Tunable Transceivers

In this section, as a demonstration of the capability of the proposed research framework, the results from the study of the elasticity of NGOA architectures are presented. A simulation study of hybrid TDM/WDM-PON under SUCCESS-HPON architecture with sequential scheduling with schedule-time framing (S^3 F) [15] has been carried out in this regard, the block diagram of which is shown in Figure 7.

![Figure 7. Block diagram of hybrid TDM/WDM-PON.](image-url)
The line rates $R_B$, $R_D$ and $R_U$ are set to 1 Tb/s, 10 Gb/s and 10 Gb/s, respectively, $RTT$ to 10 ms, and $N$ (i.e., the number of ONU$s$) to 16.

Because a user can interact with only one webpage at a time, the number of HTTP sessions is set to one, (i.e., $n_h = 1$ in Figure 6). The same is the case for a streaming video (i.e., $n_v = 1$). On the other hand, a user can run multiple FTP sessions in the background. Therefore $n_f$ is set to 10, especially to get a higher combined rate as background traffic for 10-Gb/s access out of well-established, lower-rate FTP parameters from 3GPP2 [26].

Figure 8 shows behavioral models for HTTP and FTP traffic. The parameter values are summarized in Table 1.

As for streaming video traffic, HDTV-quality “Terminator 2” VBR-coded H.264/AVC clip from ASU video trace library [27] is used, the statistics of which are summarized in Table 2. Frames are encapsulated by real-time transport protocol (RTP) and UDP before being carried in IP packets. Considering that Ethernet frames are used in data link and physical layers, the total overhead in this case is 66 octets (= RTP(12) + UDP(8) + IP(20) + Ethernet(26)). The starting frame is selected randomly from the trace at the beginning of simulation, and the whole trace is cycled throughout the simulation.

Figure 8. Traffic models for: (a) HTTP services and (b) FTP services.
### Table 1
Parameters for HTTP and FTP traffic models

| Parameters/measurements                                      | Best fit (parameters)                      |
|--------------------------------------------------------------|--------------------------------------------|
| **HTTP model [25]**                                          |                                            |
| HTML object size (byte):                                     | Truncated lognormal:                       |
| mean = 11,872, SD = 38,036, max = 2 M                        | $\mu = 7.90272, \sigma = 1.7643,\ max = 2 \text{ M}$ |
| Embedded object size (byte):                                 | Truncated lognormal:                       |
| mean = 12,460, SD = 116,050, max = 6 M                       | $\mu = 7.51384, \sigma = 2.17454,\ max = 6 \text{ M}$ |
| Number of embedded objects:                                  | Gamma:                                     |
| mean = 5.07, max = 300                                        | $K = 0.141385, \theta = 40.3257$          |
| Parsing time (sec):                                          | Truncated lognormal:                       |
| mean = 3.12, SD = 14.21, max = 300                           | $\mu = -1.24892, \sigma = 2.08427,\ max = 300$ |
| Reading time (sec):                                          | Lognormal:                                 |
| mean = 39.70, SD = 324.92, max = 10 K                        | $\mu = -0.495204, \sigma = 2.7731$       |
| Request size (byte):                                         | Uniform:                                   |
| mean = 318.59, SD = 179.46                                   | $a = 0, b = 700$                          |
| **FTP model [26]**                                           |                                            |
| File size (byte):                                            | Truncated lognormal:                       |
| mean = 2 M, SD = 0.722 M, max = 5 M                          | $\mu = 14.45, \sigma = 0.35,\ max = 5 \text{ M}$ |
| Reading time (sec):                                          | Exponential:                              |
| mean = 180                                                   | $\lambda = 0.006$                         |
| Request size (byte):                                         | Uniform:                                   |
| mean = 318.59, SD = 179.46                                   | $a = 0, b = 700$                          |

### Table 2
Overview of video traffic model

| Property/statistic     | Value                                      |
|------------------------|--------------------------------------------|
| Video clip             | “Terminator2” [27]                        |
| Encoding               | VBR-coded H.264/AVC                       |
| Encoder                | H.264 FReX                                |
| Duration               | ~10 min                                    |
| Frame size             | HD 1280 × 720 p                           |
| GoP size               | 12                                         |
| Number of B frames      | 2                                          |
| Quantizer              | 10                                         |
| Mean frame bit rate     | 28.6 Mb/s                                 |
Figures 9(a) and 9(b) show the webpage delays for the ECR reference (i.e., dedicated) model and the hybrid TDM/WDM-PON, respectively. Figures 10(a) and 10(b), on the other hand, show the DFRs of UDP streaming video for the ECR reference model and the hybrid TDM/WDM-PON, respectively. Note that for the ECR reference model, the performance measures are shown as functions of the access line rate for different numbers of users per ONU \((n)\), while those for the hybrid TDM/WDM-PON are shown as functions of \(n\) for different numbers of tunable transceivers \((N_{tx})\). In case of webpage delay, rather large confidence intervals are observed when the system load is high, i.e., when the line rate becomes low for the ECR reference model and the number of users per ONU increases for hybrid TDM/WDM-PON. This justifies the use of hypothesis testing in the proposed ECR calculation procedure in Figure 3.

Based on the performance measures shown in Figures 9 and 10 and the ECR calculation procedure described in Section 2, ECRs of hybrid TDM/WDM-PON are calculated as shown in Figure 11. The tolerance value is set to 10% of the sample mean of performance measure for the dedicated architecture in non-inferiority testing with the significance level \((\alpha)\) of 0.05. Figures 11(a) and 11(b) show that there is not much difference between the ECR values based on the webpage delay and the DFR, which indicates a strong correlation between the measures. Note that the ECR values based on both the measures shown in Figure 11(c) are the minimum of the ECR values shown in Figures 11(a) and 11(b) due to the IUT procedure in multivariate non-inferiority testing. As expected, adding more transceivers greatly improves the ECR as \(n\) increases. For example, even with one more transceiver (i.e., \(N_{tx} = 2\)), an ECR of 10 Gb/s can be achieved at \(n = 7\), while the corresponding ECR with just one transceiver drops below 1 Gb/s. On the other hand, it is remarkable that the hybrid TDM/WDM-PON with just one transceiver can achieve an ECR of 10 Gb/s until \(n\) reaches 6, which means the amount of energy consumed by transceivers can be greatly reduced compared to a dedicated point-to-point architecture which requires 16 transceivers (in case of 16 ONUs) irrespective of the level of traffic load; when \(n = 6\), streaming video traffic alone pushes about a 180-Mb/s stream into the ONU and a 2.88-Gb/s multiplexed stream into the OLT (out of 16 ONUs). Incidentally, it is found that the ECR based on webpage delay with \(N_{tx} = 3\) in Figure 11(a) shows a rather strange value for \(n = 1\). In fact, the sample mean of webpage delay in this case is 2.6242 sec (with a confidence width of 0.19 sec) and just slightly higher than other values for \(n = 1\) (i.e., with \(N_{tx} = 1, 2, 4,\) and 5), which are in the range of [2.4482 sec, 2.5751 sec]. This anomaly is gone when the tolerance value is increased to 20% of the sample mean. A longer simulation run and a bigger sample size could eliminate this anomaly. Also, the ECR values for \(N_{tx} = 1, 2,\) and 3 suddenly increase once they reach the bottom. This is because the performance measures are unreliable when the system is highly overloaded.

The same results are plotted in a different way in Figure 12, which shows the minimum number of tunable transmitters \((\text{min}(N_{tx}))\) to achieve different ECR target rates. \(\text{min}(N_{tx})\) shows monotone increasing curve as \(n\) increases. It is clear from the figure that at least an ECR of 10 Gb/s can be achieved with just one receiver until \(n = 6\). Note that when both performance measures are considered together, the resulting curves follow those based on the DFR of UDP streaming video as shown in Figures 12(b) and 12(c).

The results in this section clearly demonstrate that the hybrid TDM/WDM-PON based on the SUCCESS-HPON architecture shows a great elasticity, i.e., maintaining the same level of overall performances by varying the number of tunable transceivers for a wide range of traffic load, and results in higher energy efficiency by reducing the number of transceivers compared to dedicated point-to-point architectures (e.g., 1 to 16 in case of 16 ONUs and up to 6 users per ONU).
Figure 9. Webpage delay for: (a) ECR reference model and (b) hybrid TDM/WDM-PON. (color figure available online)
Figure 10. DFR of UDP streaming video for: (a) ECR reference model and (b) hybrid TDM/WDM-PON. (color figure available online)
Figure 11. ECR of hybrid TDM/WDM-PON based on: (a) webpage delay, (b) UDP streaming video DFR, and (c) both. (color figure available online) (continued)
Figure 11. (Continued).

Figure 12. Minimum number of tunable transmitters (min($N_{tx}$)) to achieve ECR of $R_{\text{target}}$ in hybrid TDM/WDM-PON based on: (a) webpage delay, (b) UDP streaming video DFR, and (c) both. (color figure available online) (continued)

106
Figure 12. (Continued).
5. Concluding Remarks

A new research framework for the clean-slate design of NGOA architectures and protocols has been presented, which is composed of the comparative analysis framework and the virtual test bed for experiments. The comparative analysis framework is based on the multivariate non-inferiority testing and the ECR, which is capable of statistically comparing multiple performance measures in an integrated way and providing quantification of the effective bandwidth for users of a candidate architecture with respect to a reference architecture. The virtual test bed is implemented as simulation models based on OMNeT++ and INET framework and provides a complete experimental environment with session-level traffic generation and performances gathering as well as models for the whole network protocol stack. The issues and challenges from initial studies based on the current implementation are also discussed together with plans and strategies to address them in the next version. To demonstrate the capability of the proposed research framework, numerical results from the study of the elasticity of NGOA architectures are presented, which show that the hybrid TDM/WDM-PON based on the SUCCESS-HPON architecture can manage the same user-perceived performances as those of the dedicated point-to-point architecture with the same line rate by varying the number of tunable transceivers for a wide range of traffic load. The results also demonstrate that the hybrid TDM/WDM-PON results in higher energy efficiency by reducing the number of transceivers compared to dedicated point-to-point architectures.

Note that there is a major implication of the proposed research framework: the way of comparing network architectures and protocols and presenting their performances would be dramatically changed. For instance, using the ECR as a reference (i.e., under the same ECR by adjusting network configurations like the number of users), it is possible to objectively compare the issues of cost and energy efficiency of candidate architectures, which is critical for the clean-slate design of NGOA. In addition, the proposed research framework could greatly help network service providers do proper dimensioning of their NGOA before the actual deployment in the field, especially because the notion of ECR is based on user-perceived performances.

Although the mix of traffic and their parameters in the proposed research framework could be a good starting point, they need to be refined further based on the data from large-scale simulations and/or, if possible, field trials in order to have a standard set of traffic models for NGOA—like those for wireless networking [26, 29]. Other important topics not discussed in this article are the inclusion of upstream traffic (e.g., peer-to-peer applications) and the use of high-speed variants of TCP [30] in the virtual test bed.

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Biography

Kyeong Soo Kim received his BS, ME, and PhD in electronics engineering from Seoul National University, Seoul, Korea, in 1989, 1991, and 1995, respectively. From 1996 to 1997, he was engaged in the development of multi-channel asynchronous transfer mode (ATM) switching systems as a post-doc researcher at Washington University in St. Louis, Missouri, where he also taught undergraduate and graduate students as an instructor and an adjunct professor. From 1997 to 2000, he worked with the passive optical network (PON) systems R&D organization of Lucent Technologies and was involved with development of ATM-PON systems, which won the 1999 Bell Labs President’s Silver Award. From 2001 to 2007, he was with STMicroelectronics, working as a principal engineer, representing STMicroelectronics in various standard bodies, including FSAN, ITU-T, and IEEE 802.11/16 working groups; from 2001 to 2006, he also took the position of STMicroelectronics Researcher-in-Residence at the Stanford Networking Research Center (SNRC) and worked on “optical internet” and “next-generation access networks” projects together with students and faculties at Stanford University. Since 2007, he has been working at the College of Engineering, Swansea University, Wales, UK, as a senior lecturer in networking, where he leads the Hybrid Networking Research Laboratory (HNRL) and carries out research in next-generation optical access (NGOA) and hybrid optical-wireless networks. He is a member of IEEE.