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Bandwidth allocation for multiple IPTV users sharing the same link: a case study of Telecom of Kosovo

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Abstract: Almost all operators today are facing constant requests for multiple video services in a single household. In these situations, video services have to compete for finite network bandwidth and other equipment resources. Each of them requires different bandwidth capacities. This dynamic behavior can jeopardize both quality of service and quality of experience. One should keep in mind that some video channels require more bandwidth than others. Telecom of Kosovo (TK) is facing the same issues. The encoders at TK are not scalable and they treat all video streams equally, without taking into consideration the fact that some video streams require higher bit rates than others. This is the reason why there is a need to implement new and intelligent algorithms that would help fairly share bandwidth between different users, depending on the requests for different video streams. In this paper, we present a new algorithm for rate allocation that optimizes a weighted sum of the perceptual quality of all video streams subject to bandwidth constraints. We try to come up with concrete suggestions for a practical implementation of this algorithm, focusing on implementation costs and improving the quality. The proposed algorithm will consider the impact of spatial, temporal, and amplitude resolution (STAR) of a coded video on both bit rate and quality. This algorithm will also determine the optimal rate and corresponding STAR for each video.

Key words: Internet protocol television, quality of service, quality of experience, spatial, temporal, and amplitude resolution

1. Introduction

Service providers worldwide are looking for different ways to deliver high-quality Internet protocol television (IPTV) services. Customers today require more than one set-top box (STB) per household. Therefore, it is a real challenge for operators to offer such high-quality services.

Telecom of Kosovo (TK) is an incumbent fixed telecommunications service provider. In its efforts to keep the leading position in Kosovo's competitive telecommunication market, TK has implemented an advanced IPTV platform. The trend toward increasing the number of customers and their requirements for IPTV services will very soon exceed the gigabits per second capacities of backbone and in-core networks. While there is competition for bandwidth, video channels may suffer in terms of quality [1–4]. TK has implemented advanced technology in the core part to offer such services. However, the main challenge lies in access and the edge network (backbone network). The challenge of providing quality services increases even more with the increasing users' demands

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for different IPTV services, including high-definition television (HDTV) [2–10]. Implemented technological solutions in TK equally divide bit rates among all households and among all video classes. In this case, we might have problems with video channels that have different bit rates. This problem will be even greater in cases where one household requires more than one video stream [1]. TK is facing similar requests on a daily basis. To overcome these issues, intelligent algorithms need to be designed in order to share the bandwidth fairly among different users inside one household. There is a possibility that within the same household one STB might be of good quality, whereas others might not. For high-motion videos, the system should normally assign more bandwidth, whereas for low-motion videos the system should assign lower bandwidth values. Hence, as multiple videos with different characteristics are streamed over the same access link, the system should allocate different bit rates to equalize their quality at the receivers [1].

In this paper, we will analyze the rate allocation among multiple IPTV videos when either the access link or a backbone link has insufficient bandwidth to support high bit rate videos. Our proposed rate allocation algorithm uses an analytical rate and quality models [1]. We will consider the impact of spatial (i.e. frame size (FS)), temporal (i.e. frame rate (FR)), and amplitude resolution (controlled by the quantization step size or QS-STAR jointly). Such models are critical for applications where the target video rate range is very large [1]. The algorithms that we proposed in paper [1] performed better compared to the benchmark algorithm (the algorithm implemented in the IPTV system in TK). The main objective of this study was to further improve these algorithms.

2. IPTV technology implemented at TK

The access network at TK is based on copper. This network is restrictive in terms of offering high-quality IPTV services. TK has implemented advanced technologies for offering such services like an asymmetric digital subscriber line (ADSL), ADSL2+, and, more recently, very-high-bit-rate digital subscriber line (VDSL) technology. In addition, TK is implementing gigabit passive optical network (GPON) technology. The IPTV platform implemented at TK is shown in Figure 1. This platform is implemented in two separate locations, which also provides redundancy for the application platform.

The core network offers gigabit capacity; however, there is a need to find solutions for better bandwidth usage. In the TK IPTV platform, Moving Picture Experts Group/Advanced Video Coding (MPEG-4/AVC) encoders were implemented. The encoding system implemented at TK is divided into AVC standard and high definition. Each encoder has a dual-IP output to feed two networks for redundancy purposes. The encoder system supports MPEG-2 and MPEG-4, as well as standard definition (SD) and high definition (HD) formats. Since users are utilizing IPTV services via different equipment with different processing power and different resolution formats, we need to implement more advanced encoding systems. Implementing a scalable video coding (SVC) system [11] is essential in order to fulfill users' requirements.

3. Problem formulation for bandwidth usage optimization

In this section, we will discuss problem formulation for maximizing bandwidth usage under the assumption that there are five different devices trying to access different services (different video channels). Each video is encoded with JSVM [12–15] using combined spatial and temporal scalabilities with three spatial layers (4 CIF, CIF, and QCIF) and three temporal layers (30, 15, and 7.5 Hz) [11,16]. If there are five devices in one household, each trying to access different video services, the access link bandwidth should be divided fairly between the five users. We will formulate the problem under the assumption that all of these users are simultaneously

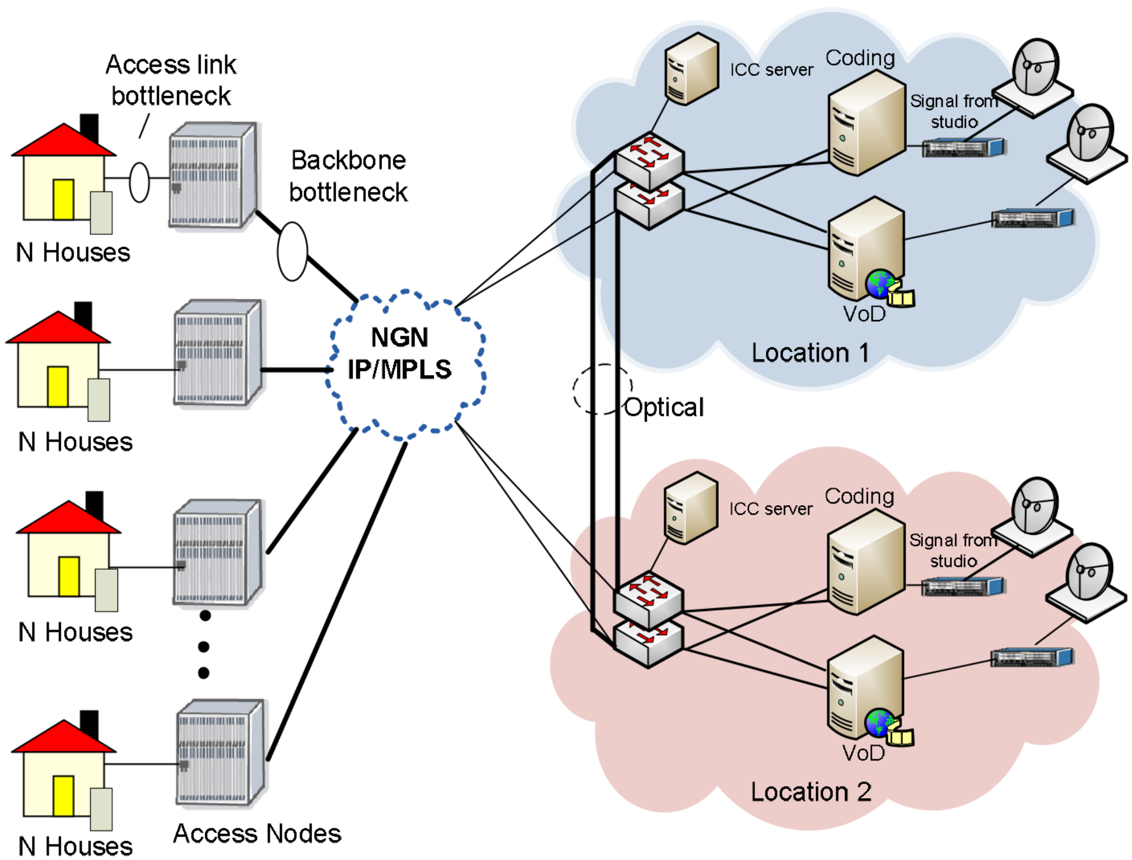

Figure 1. IPTV platform implemented at TK.

requiring these channels. The idea is to maximize bandwidth usage and not have video streaming interruption. This problem requires maximizing bandwidth usage in order to increase video quality. Bandwidth allocation is restricted to these constraints:

$$st. \sum_{i=1}^{I} R_i \leq C, \tag{1}$$

$$s.t \;\; R_i < R_{max} \quad . \tag{2}$$

Eq. (1) means that the bit rate of all video channels should be equal to or less than the total bandwidth (C = 40 Mbps).

Eq. (2) means that every video's bit rate should be under a maximum value for that video (SD or HD videos, according to the assumptions that we made).

We have used the same analytical rate and quality models for algorithm development as in [1]. Specifically, the rate model relates the video rate with frame size s, frame rate$t$, and quantization step size q by Eq. (3):

$$R\left(q,s,t\right) = R_{max}\left(\frac{q}{q_{min}}\right)^{-a}\left(\frac{t}{t_{max}}\right)^{b}\left(\frac{s}{s_{max}}\right)^{c} \quad , \tag{3}$$

where q_{min}, s_{max}, and t_{max} are the minimal QS, maximal FS, and maximal FR, respectively. R_{max} is the video rate when the video is coded at q_{min}, s_{max}, and t_{max}. We assume that R_{max} can be accurately estimated for real-time encoding or can be obtained from precoded streams for scalable video adaptation. The quality model relates the video quality with $s, t,$ and q by Eq. (4):

$$Q(q,s,t) == \frac{1-e^{-\alpha_q\left(\frac{q_{min}}{q}\right)^{\beta_q}}}{1-e^{-\alpha_q}} \frac{1-e^{-\alpha_s\left(\frac{s}{s_{max}}\right)^{\beta_s}}}{1-e^{-\alpha_s}} \frac{1-e^{-\alpha_t\left(\frac{t}{t_{max}}\right)^{\beta_t}}}{1-e^{-\alpha_t}} \quad , \tag{4}$$

where $\beta_q = 1$, $\beta_s = 0.74$, $\beta_t = 0.63$, $\alpha_s(q) = \bar{\alpha_s}(v_1 QP(q) + v_2)$ when $QP \geq 28$ and $\alpha_s(q) = \bar{\alpha_s}(28v_1 + v_2)$ when $QP < 28$, with $v_1 = -0.037$, $v_2 = 2.25$.

In this paper, we have used the same model forms for single-layer and scalable videos. These test videos were coded with the H.264/SVC algorithm. Rate and quality models for the two videos are shown in Tables 1 and 2. The two tested videos are the following: "Ice" with $R_{max} = 2183$ kbps (R_{max} is content dependent) and "Harbour" with $R_{max} = 7659$ kbps.

Table 1. Rate model parameters for tested videos.

Rate parameters	Ice	Harbour
a	0.68	0.97
b	0.755	0.99
c	0.63	0.61
R_{max} (kbps)	2183	7659

Table 2. Quality model parameters for tested videos.

Quality parameters	Ice	Harbour
α_q	5.61	9.65
α_s	3.68	4.58
α_t	3.00	2.83

4. Rate allocation under both the access link and edge network bandwidth constraint: the first scenario

In the previous algorithm that we presented in [1], there was always some residual bandwidth (RBW) when we tried to reach maximum quality. This is because for different STAR combinations there are different bit rate ranges, and each household can only choose from these ranges. In this paper, we will try to further improve the algorithm presented in [1]. The algorithm implemented in [1] will be called benchmark2, whereas the benchmark algorithm from [1] will be called benchmark1 (the algorithm implemented in real IPTV systems at TK). In [1], we proved that benchmark2 results in better quality and bandwidth utilization compared to benchmark1. The idea for further improving the benchmark2 algorithm originates from the fact that there is RBW. We will try to find a solution by adding this bandwidth to the lowest bandwidth level assigned by the benchmark2 algorithm. However, we will first try to decrease the RBW as much as we can, and anytime there is high RBW, we will try to separate this bandwidth in households that receive the lowest quality service.

We will analyze a scenario in which we have two bottlenecks: one in the backbone link and another one in the access link (from the access network (AN) to the household). Let us assume that we still have two sets of constraints. The backbone constraint is G = 40 Mbps, and the access link constraint is C = 10 Mbps. We will assume that there are 10 households (J = 10) connected to one particular AN and each household simultaneously requires five videos. We will take into consideration that we have only two video classes with the characteristics of Ice (Rmax = 2.183 Mbps) and Harbour (Rmax = 7.659 Mbps). Videos with the characteristics of Ice will be named CL1 (Class 1), whereas videos with Harbour characteristics are named CL2 (Class 2). Since we only have two video categories, it will be much easier to take the combinations of videos for each household. According to this assumption, all IPTV channels can be in one of these two classes (CLs). For example, 50 TV channels that require a lower bit rate will belong to CL1, whereas other TV channels requiring a higher bit rate will belong to CL2. One household can have only TV channels that have CL1 characteristics, CL2, or a combination of CL1 and CL2. Considering the different video combinations that one household might require, there are some compromises that should be made while using the benchmark2 algorithm. For households requiring five videos with CL2 characteristics [5 Harbour], there is a possibility to allocate the lowest bandwidth value, even though the Harbour video combinations require the highest bit rate. The proposed algorithm can be shown as follows:

Proposed algorithm

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1. Allocate backbone bandwidth of 40 Mbps equally to each of the 10 houses, which gives 4 Mbps in each access link (AN-household).
2. Find maximum quality and related total bite rate $R_{\min k i_k j_{i_k}}$ for each kind of video content combination under a total bandwidth constraint of 4 Mbps.
3. Select randomly (uniform distribution) how many houses a_k demand which kind of video sequence combination.
4. Under backbone constraint of 40 Mbps find out the

$$\text{residuebandwidth} = 40\,\text{Mbps} - \sum_{k=1}^{6} a_k \times R_{\min k i_k j_{i_k}}$$

5. Find all available RSTAR combinations $R_{k i_k j_{i_k}(q,t,s)}$ and related $Q_{k i_k j_{i_k}(q,t,s)}$ having rate within the range of $R_{\min k i_k j_{i_k}}$ and 10 Mbps constraint in access link.

$$R_{\min k i_k j_{i_k}} \leq R_{k i_k j_{i_k}(q,t,s)} \leq \min\left(\text{residuebandwidth} + R_{\min k i_k j_{i_k}},\ C\right)$$

6. Do exhaustive search within the bandwidth range of 40 Mbps with combination of condition 5 and find out the combination that gives the best total quality.

$$Q_{\text{optimize}} = ^{\max} \sum_{k=1}^{6} \sum\nolimits_{i=1}^{I} m_{ki} \times Q_{k i_k j_{i_k}(q,t,s)}$$

$$\sum_{i=1}^{J} m_{ki} = a_i$$

$$\text{s.t.} \ \sum_{k=1}^{6} \sum\nolimits_{i=1}^{I} m_{ki} \times R_{k i_k j_{i_k}(q,t,s)} \leq G$$

In the above algorithm, k = [1,2,3,4,5,6] represents the six video combinations (Table 3), m_{ki} represents the number of households of STAR combinations for each video content combination, G = 40 Mbps, C = 10 Mbps, and i = [1–I], which is the number of STAR combinations for each video content combination.

For the proposed algorithm, we will set a threshold for quality of 0.5 in order to avoid the possibility of using values that are below 0.5. Lower RBW means higher quality. After this, we have to demonstrate whether

Table 3. Possible video combinations per household.

No. of combination	Possible video combinations				
1	CL1	CL1	CL1	CL1	CL1
2	CL1	CL1	CL1	CL1	CL2
3	CL1	CL1	CL1	CL2	CL2
4	CL1	CL1	CL2	CL2	CL2
5	CL1	CL2	CL2	CL2	CL2
6	CL2	CL2	CL2	CL2	CL2

total bandwidth usage is equal to or less than the bandwidth constraint of 40 Mbps using all possible STAR combinations. We will then extend the exhaustive search in order to have minimum RBW. This will increase the overall quality. We will call this algorithm the proposed algorithm. Following this, we have to check whether total capacity exceeds the supposed value of 40 Mbps using all possible combinations of the STAR values.

For the algorithm implemented at TK (benchmark1) for this scenario, we will assign a maximum of 4 Mbps per household (10 households $\times$ 4 Mbps = 40 Mbps). Furthermore, we will equally split the 4 Mbps among five videos, leading to 0.8 Mbps for each video. The assigned bit rates used are listed in Table 4.

Table 4. Rate allocation for the benchmark1 algorithm.

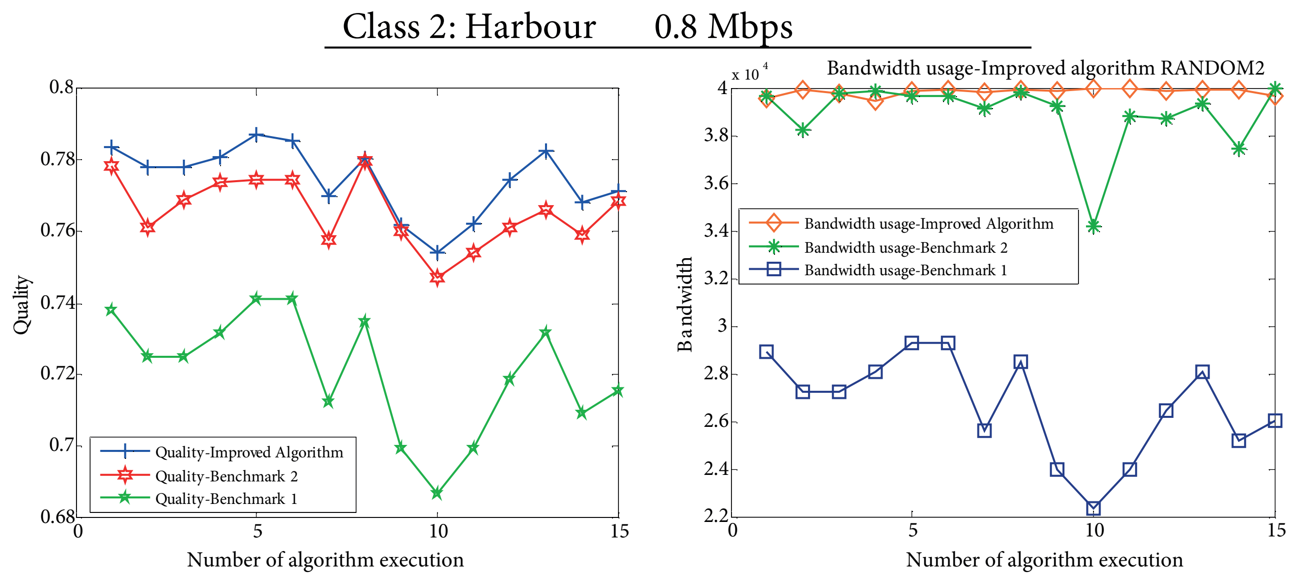
Video classes	Assigned Bit rate
Class 1: Ice	0.8 Mbps
Class 2: Harbour	0.8 Mbps

4.1. Results and discussion for the first scenario

For this scenario, the rate allocation cannot be independently determined for each household. It is not good practice to equally split the backbone capacity among all households as the video combinations chosen by some households may require a much higher bandwidth in order to achieve acceptable quality. After executing this algorithm, we will obtain the results for quality and bandwidth usage for benchmark2, benchmark1, and the proposed algorithm. These results show how much this algorithm improves the benchmark2 algorithm in terms of quality and bandwidth usage.

From Figure 2, it can clearly be seen that the proposed algorithm performs better in terms of quality and bandwidth usage compared to both the benchmark1 and benchmark2 algorithms. Regarding perceived quality, the proposed algorithm performs better after each algorithm execution, except for one case when it presents the same performance as benchmark2. After each simulation, the proposed algorithm also presents higher bandwidth usage values compared to benchmark2. In general, the proposed algorithm performs better in terms of quality and bandwidth usage compared to the benchmark2 algorithm. In order to predict the quality that each customer will have, it is important to analyze the bandwidth allocation for each user. In Figure 3, we will show how the distribution of bandwidth is done in a household that simultaneously receives five different video channels. This scenario is a bit uncommon for Kosovo, but the idea was to test the performance of the proposed algorithm in such cases. Figure 3 shows bandwidth distribution after 15 executions of the proposed algorithm.

In Figure 3, we can see how the bandwidth is divided in the households that have different combinations between two video classes (Ice-CL1 and Harbour-CL2). Since Harbour has a bigger R_{max} than Ice, we tried to allocate bigger values to Harbour. This proposed algorithm also takes into consideration this fact and always allocates a higher bandwidth for CL2 than for CL1.



a) Quality b) Bandwidth Usage

Figure 2. Comparison between benchmark1, benchmark2 and the new algorithm (proposed algorithm): a) quality b) bandwidth usage.

In every case, we will have small RBW values. Figure 4 shows this RBW for the proposed algorithm. This RBW had larger values for the benchmark2 algorithm compared to the values that we gained after we executed the proposed algorithm. Therefore, the main aim of the proposed algorithm is to decrease RBW while increasing overall quality.

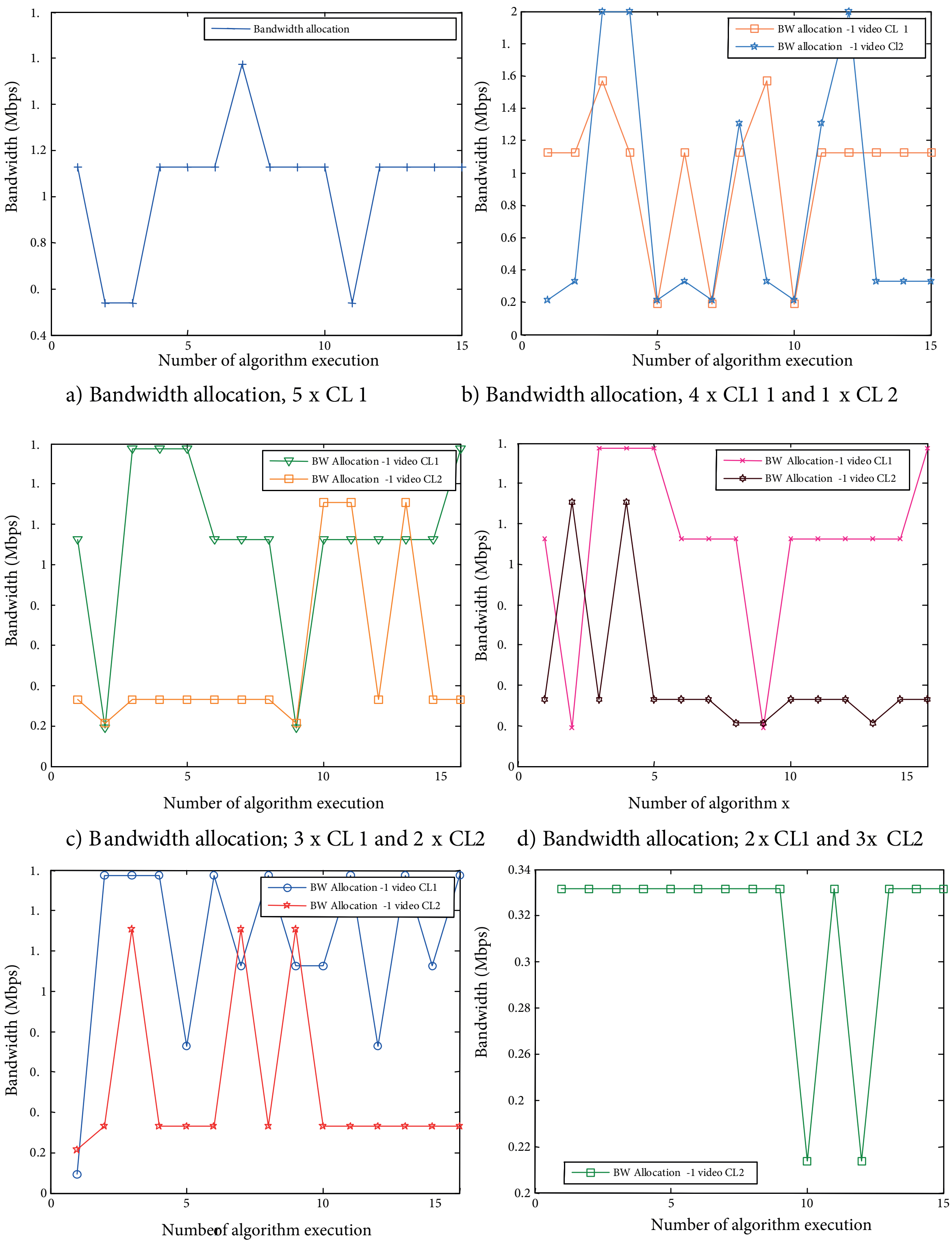
The distribution of TV channels for each user in the same household can be seen in Figure 5. These are the results after implementation of the proposed algorithm. From this figure, it can clearly be seen what capacity belongs to each user inside the house. Since the bandwidth constraint is 40 Mbps, we will have low bandwidth values assigned for each user inside the house. As a result, the quality will not be so high in this scenario.

5. Rate allocation under a 80 Mbps constraint in the backbone link: the second scenario

In this scenario, we treat the same problem as in the first scenario, but here we assume the constraint of 80 Mbps in the backbone link (ESS-DSLAM). We decided to increase this value, since for 40 Mbps the quality was not satisfactory. The values for benchmark1 will now be increased to 1.6 Mbps for each video channel. This is because 80/10 (houses) = 8 Mbps is the maximum capacity for each house. We supposed that five video channels' transmissions were simultaneously playing in each house; thus, 8/5 = 1.6 Mbps. Therefore, the benchmark1 algorithm is the standard one and takes values similar to this situation. In this case, we have also supposed that all video channels belong to two classes. Our goal was to analyze benchmark1, benchmark2, and the proposed algorithm.

5.1. Results and discussion for the second scenario

After executing the algorithm, we can see the results in Figure 6. Even in this scenario, we demonstrate that the new algorithm performs better than both benchmark1 and benchmark2.



e) Bandwidth allocation; 1x CL1 and 4x CL2 f) Bandwidth allocation; 5x CL2

Figure 3. Bandwidth allocation for each customer with the improved algorithm: a) 5 CL1 videos, b) 4 CL1 videos and 1 CL2 video, c) 3 CL1 videos and 2 CL2 videos, d) 2 CL1 videos and 3 Cl2 videos, e) 1 CL1 video and 4 CL2 videos.

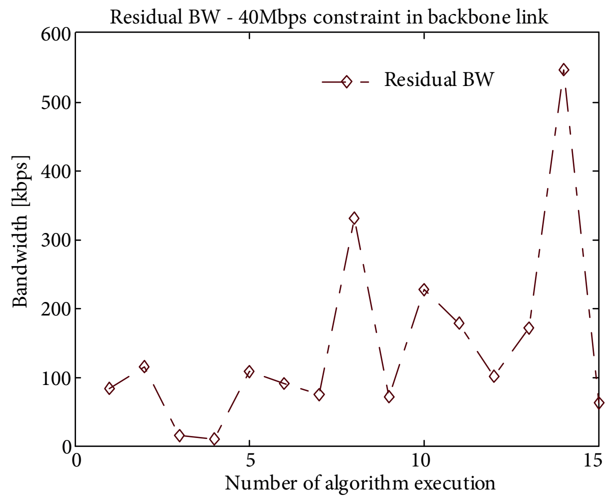


Figure 4. RBW for a backbone link at 40 Mbps.

In terms of quality, the proposed algorithm performs better after each algorithm execution compared to benchmark2. In addition, after each simulation, the proposed algorithm presents much higher bandwidth usage values compared to benchmark2. We can clearly conclude that, even in this scenario, the proposed algorithm performs much better compared to the benchmark2 algorithm.

In this section, we also discuss bandwidth allocation for each user. By executing the proposed algorithm, we will see how the bandwidth is assigned to users that require five video channels simultaneously. Table 5 presents the details of service distribution in each household after the proposed algorithm is executed.

Table 5. Distribution of services in every house.

Video	5 videos	4 videos	3 videos	2 videos	1 video	0 videos
combinations	CL1, 0 CL2	CL1, 1 CL2	CL1, 2 CL2	CL1, 3 CL2	CL1, 4 CL2	CL1, 5 CL2
No. of houses	2	2	1	1	1	3

It is clear that even in this scenario there is some RBW. As shown in Figure 7, the RBW does not have large values (kbps ranges), but the idea is that even those small values will be spread out in each household. In this way, we can achieve better quality results.

By increasing the backbone link capacity from 40 Mb to 80 Mb, we can clearly see that quality will be increased and, at the same time, capacity will be increased, as well, in terms of Mbps per household. The comparison between these two scenarios (per household) is shown in Figure 8. The comparison between these two scenarios is made in order to show how bandwidth allocation is done for these two scenarios, and the idea was to test this algorithm for both cases.

As we can see from Figure 8, for every video combination that one household might require, there will be a higher bandwidth assigned for the second scenario compared to the first scenario. It is clearly demonstrated that for households that require all CL1 video channels, the first and second scenarios are closer to each other in terms of bandwidth assignment. Conversely, in instances where customers require video combinations from CL1 and CL2, but the demand is such that the number of channels that belong to CL2 is greater than the number of channels that belong CL1, the proposed algorithm assigns much more bandwidth in the second scenario. This means that the proposed algorithm is somehow intelligent and assigns bandwidth according to the customer's requests.

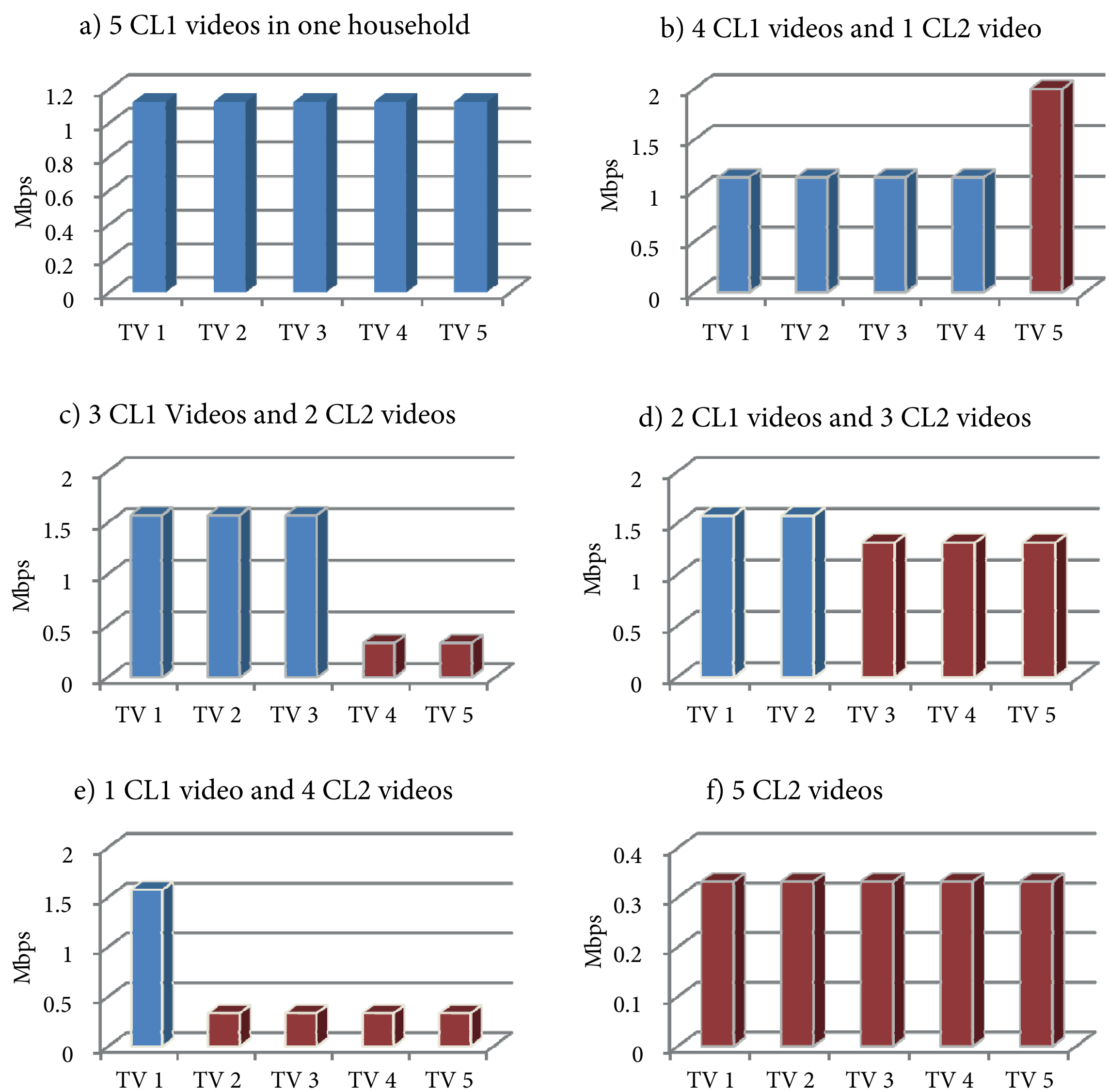
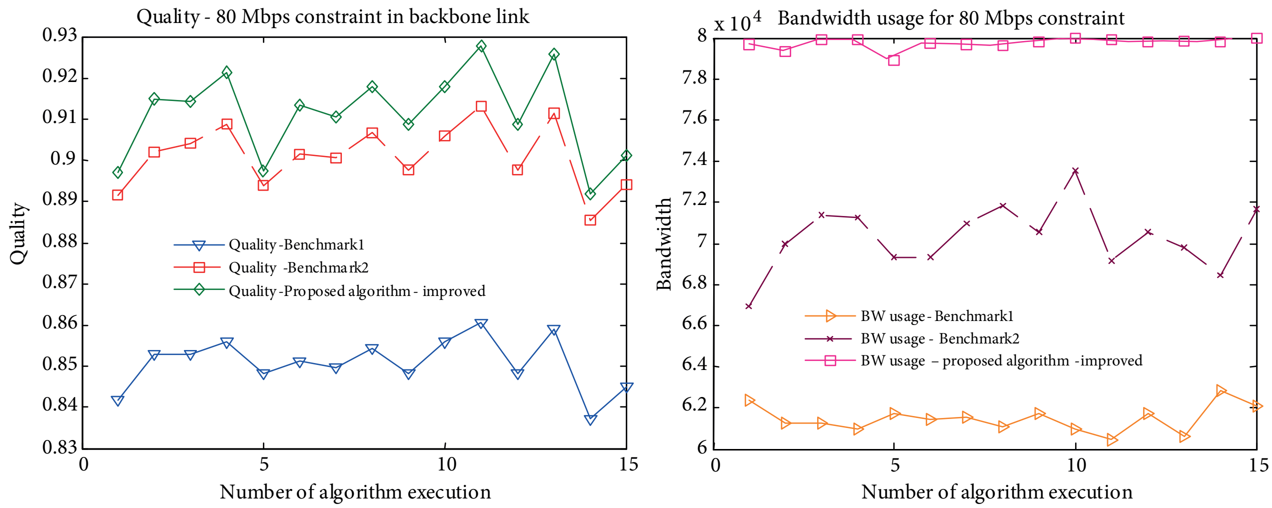


Figure 5. Distribution of TV channels for each user inside the same house: Scenario 1 at 40 Mbps from ESS-DSLAM (backbone link).

5.2. Implementation of the proposed algorithm at TK

While this proposed algorithm performs better in both scenarios compared to the benchmark1 and benchmark2 algorithms, it is important to analyze the place where the algorithm needs to be implemented, i.e. the TK IPTV platform. At TK, there are approximately 250 ANs managed by a centralized server (CS). Customers are connected directly to the ANs, whereas the CS is located at the headend part of the IPTV platform. Each AN is aware of its user groups and of the services that these users request. The AN sends these requests to the CS where the proposed algorithm should be implemented. The algorithm determines the bit rate of the requested video channel and sends this information to the video encoders, so the video can be encoded in real time at the desired STAR values. Implementing the algorithm in this server is commercially a favorable solution as there is no need for other servers. Hence, this solution is very cost-effective.



a) Quality

b) Bandwidth usage

Figure 6. Quality and bandwidth usage comparison between the old algorithm, the proposed algorithm, and the benchmark algorithm: a) quality, b) bandwidth usage.

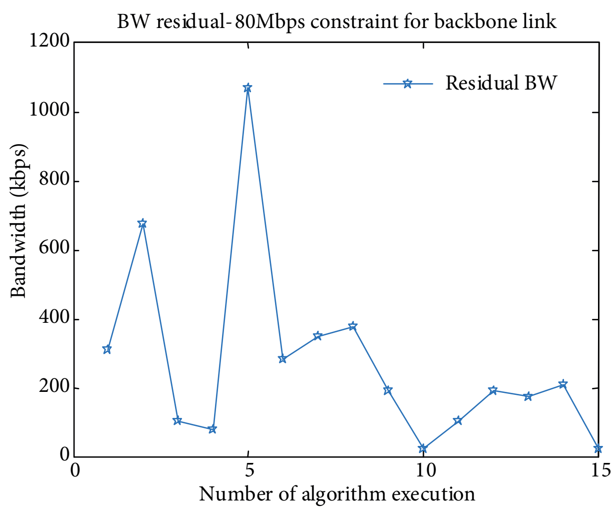


Figure 7. RBW for a backbone constraint of 80 Mbps.

6. Conclusion

At TK, there is exponential subscriber growth. Since the bandwidth and processing resources are finite at TK, it will be hard to ensure quality among all users in the near future. These restrictions can subsequently cause quality degradation. Other problems in the IPTV TK network are dynamic subscriber behaviors and different video classes with different requirements for bit rate.

In this paper, we discussed different ways of solving such problems at TK. We developed a new algorithm with MATLAB, taking into consideration the impact of spatial, temporal, and amplitude resolution (controlled by quantization step size or QS-STAR). The idea for implementing such an algorithm derived from the fact that with the benchmark2 algorithm [1] we achieved better performance than with the benchmark1 algorithm. However, we noticed that we could improve further because for the benchmark2 algorithm we had some values of RBW. The goal was to lower this RBW as much as possible, thus increasing quality. In addition, we set a

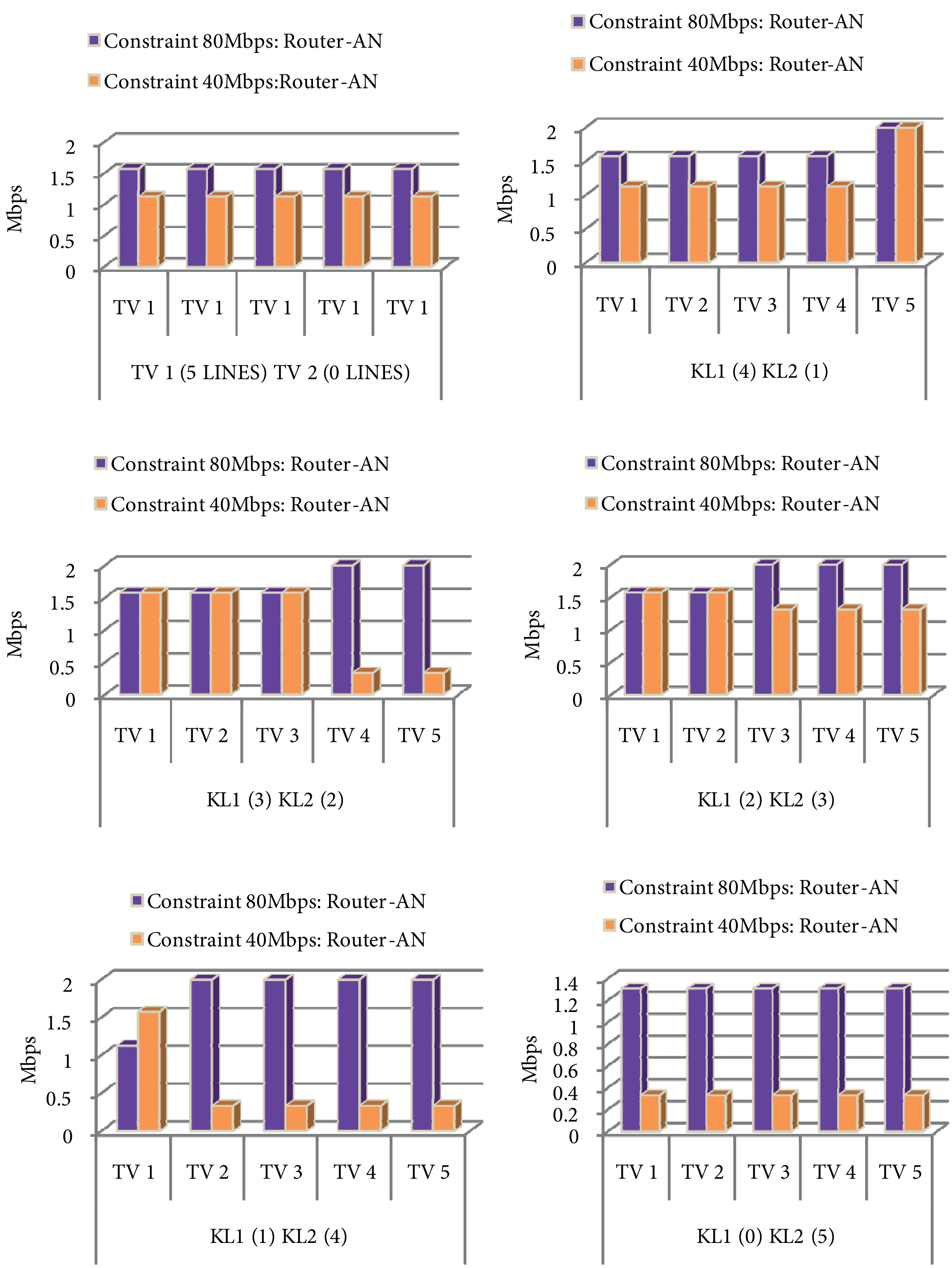


Figure 8. Comparison of capacity distribution for the two scenarios.

quality threshold of 0.5 in order to exclude values below this threshold. We managed to lower the RBW and increase overall quality. The proposed algorithm was tested in two scenarios: at bandwidth constraints of 40 Mbps and 80 Mbps. In both scenarios, there were two bottlenecks: one in the access link and the other in the backbone link. According to the results following algorithm execution, we can conclude that the new algorithm performs better than benchmark1 and benchmark2 in both tested scenarios.

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