

# Scheduling Strategies Support for Multiple VPNs over Broadband PLC Access Networks

Le Phu Do and Ralf Lehnert

**Abstract**—Broadband Powerline Communications (BPLC) uses the infrastructure of the electrical power lines to provide broadband access to the end-users. A BPLC system supports users with multiple services, utilizes the scheduler to manage the available network transmission capacity via a bandwidth broker, and delivers the access right to the users based on their requests. Over the BPLC network, provided by an electrical power supplier, each ISP can rent a part of the access network to provide different services to its own customers. All the customers of an ISP supported via a VPN embedded inside the BPLC network. The customers inside a VPN produce different traffic streams with various quality requirements. A BPLC network may consist of several cells, each is configured as a master-slave system. The master station in a BPLC cell allocates the limited bandwidth to its slaves, based on the services and agreement with the ISPs.

Since the BPLC network uses a shared medium, the problem arises when there is not enough available transmission capacity to satisfy all the requests from the users at the same time. Therefore, this paper proposes scheduling strategies to distribute resource to users in different VPNs. The scheduling strategies have the objective to maximize the efficiency of the available bandwidth, while maintaining the fairness between users inside a VPN and also the fairness between different VPNs. The scheduling problem is formulated as an optimization problem in order to be solved by enumeration methods and a heuristic algorithm. The performances of the strategies are presented and analyzed.

**Index Terms**— Broadband Powerline Communications (BPLC), Carriers' Carrier Model, Fairness, Virtual Private Network (VPN).

## I. INTRODUCTION

Broadband Powerline Communications (BPLC) has gained a lot of interest because the normal electric power line is utilized for transmission also communication signals. With different transmission techniques, e.g. provided by the OPERA (Open PLC Research Alliance) Consortium [1], the HomePlug Alliance [2] – Panasonic, and currently the work from the IEEE P1901 working group [3], a BPLC network consists of several sub-networks, called BPLC cells. Each BPLC cell is configured as a master-slave system, and provides access network with speeds of up to 200 Mbps [1][2]

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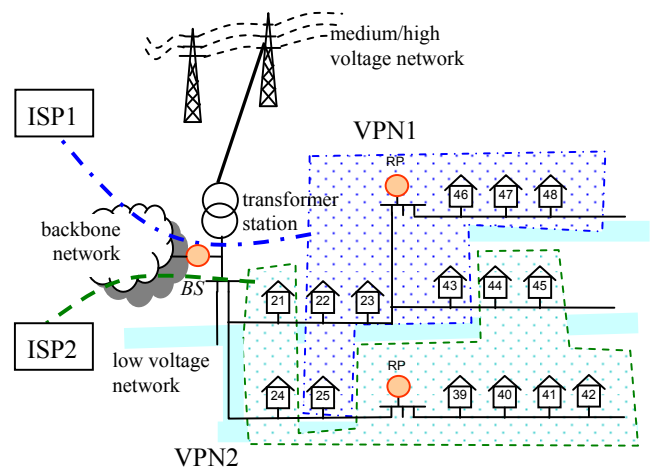


Fig. 1. BPLC network with multiple VPNs

to the end-users. The master station of the cell (called Base Station or BS) has a scheduler to manage the available transmission capacity to grant access to the medium to its slaves in both uplink and downlink transmission directions. The BS has to find the way to divide the limited transmission capacity to its slaves while maintaining the QoS (Quality of Service) requirements of the services.

We consider the so-called “carriers’ carrier model” over the BPLC as described in [4]. Following this model, the BPLC is built and provided by the electrical power supplier who provides a virtual network to each ISP (Internet Service Provider). All the customers of an ISP are assigned into a VPN (Virtual Private Network) embedded inside the BPLC network. The electrical power supplier who provides the VPN access is called VPN provider. An example of a BPLC network with two VPNs is shown in Fig. 1. A base station is installed in the transformer station to provide network access to the users located inside the low voltage network. When the user is located near the BS, the communication can be organized directly between user and the BS. Otherwise, one or several repeaters (RP) are necessary to span the network. The term “user” is also used to mention the power line equipment installed in the customer’s premise. The BS is connected to the backbone network via an optical link or via BPLC over medium voltage lines.

There are different methods for configuring multiple VPNs for multiple service providers as specified in [4][5][6],

including IP (Internet Protocol) range selection, VLAN (Virtual Local Area Network) tagging, or group of traffic from users belonging to an ISP via an access port. In this paper, a BS in our reference system aggregates all traffic from its slaves and sends to the corresponding ISP regardless the VPN configuration method. In order to solve the problem inside the BPLC network, we assume that there is no congestion in the backbone connection. All the users associated a VPN will be served by the ISP via the management of the base station.

When the available transmission capacity is not enough to satisfy all the requirements from the users, a sharing strategy has to be applied. In general, there are two solutions for dealing with this situation [7]. If the new request service is important, the scheduler can drop a connection with lower priority to gain some bandwidth for the new service. Another solution is to reduce bandwidth from all available connections to get bandwidth for a new one. The later solution may not be suitable for the network contains hard real-time services that do not work with a given bandwidth lower than a minimum requirement. A good sharing strategy has to ensure the quality of the granted service and fairness between multiple users.

Among several sharing strategies presented in [8], [9], one well known strategy used by the BS is the “round robin” method. The incoming packets are stored in the different queues for different users and kinds of services. The queues are served in a cyclic order. Other derived methods of the round robin, e.g. weighted round robin or hierarchical round robin, consider a priority for each queue, which is expressed by the frequency and duration for serving a queue. In order to analyze the scheduling requirement in a BPLC access network regarding the QoS requirement for different type of services, we consider the service classes in accordance with the OPERA specification.

In this paper, we define the benefit a user gets from each granted service and calculate the overall benefit of the scheduling solution. The scheduling solution has to maintain the fairness between users in the same VPN (intra-VPN fairness) and the fairness between VPNs (inter-VPN fairness). We apply the weighted round robin mechanism and propose a best benefit selection method to find the sharing solution. Further, the resource sharing strategy is formulated as an optimization problem and solved.

The organization of this paper is as follows: section II presents the realization of multiple VPNs over the BPLC network. Typical characteristics of the bandwidth sharing over BPLC network and the approach to evaluate a scheduling strategy are proposed in section III. The proposed solutions for solving the optimization problem are introduced in section IV. The performances of the solutions are evaluated and the results are analyzed in section V.

## II. MULTIPLE VPNs OVER THE BPLC NETWORK

### A. The Carriers' Carrier Model

In reality, the carriers' carrier model is applied for the case

where there are several telecom service providers buy or rent bandwidth from an infrastructure provider. These service providers have to share a same infrastructure and provide their services to their own customers. Each customer may freely choose its service providers.

The task of a VPN provider is to design the network infrastructure, providing backhaul and maintaining the total network. The ISP in its turn has to provide value added services like internet, VoIP, games, and video conferences, etc. to its customers. Each ISP can provide specific offers to the end customer, e.g. different maximum internet access speeds according to different prices. Since several ISPs can provide the same services with different prices and bandwidth needed, the customer carrier gets the customer choices for its appropriate requirements.

### B. Multiple VPNs supported by the BPLC

Multiple VPNs is supported by the BPLC, e.g. as we consider the OPERA description in [1]. Following this description, the data packet to be transmitted over the power line is called OPERA-Packet. Each OPERA-Packet is equipped with a field to carry the VLAN-Tag. In the downlink direction, from BS to user, the Ethernet packet is translated to the OPERA-Packet and the access port of the ISP is translated to corresponding VLAN-Tag. Only users who are assigned to the corresponding VPN can receive the packet with the correct VLAN-Tag. In the uplink direction, from user to the BS, the OPERA-Packet is translated back to the Ethernet packet and the VLAN-Tag is translated to the corresponding port of the ISP.

### C. Traffic control in a Base Station

When applying the carriers' carrier model, the VPN provider has to maintain the scalability of the bandwidth between ISPs. Each ISP has a specific weight reflecting its priority when sharing resources because of e.g. its local topology or contract with the VPN provider. A traffic control implemented in a BS is presented in Fig. 2. The incoming traffic in the downlink direction, after being accepted by the connection admission control block, will be put into different queues based on the destination and type of service by the

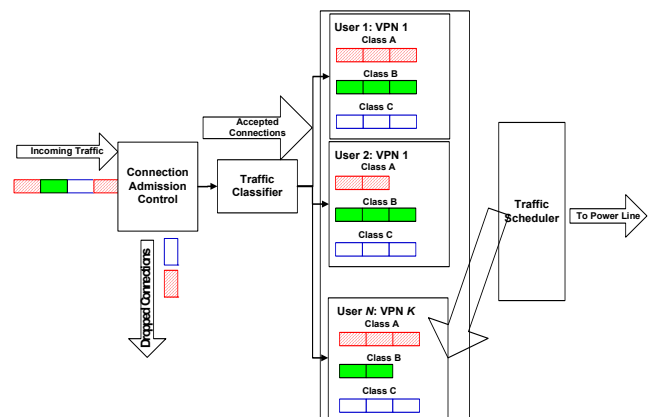


Fig. 2. Traffic control in a Base Station

traffic classifier block. The traffic scheduler serves the queues based on the class of service parameters and the weights of the ISPs.

### III. BANDWIDTH SHARING AND PROBLEM FORMULATION

#### A. Bandwidth Sharing Issues

When a user connects to the network, a logical connection from this user to the BS is established. In order to provide the QoS guarantee for each type of service, a certain amount of the transmission resource will be assigned to each transmission session. Each service is classified in to a specific service class in which the QoS parameters like throughput, latency, transmission reliability, etc., are defined. For example, the throughput required for VoIP according to ITU-G.711 is 64kbps with an end-to-end delay smaller than 150ms, or a video conference flow requires a throughput of 128kbps.

When a new service is initialized from a user, this user sends a request to its BS and waits for the new bandwidth assignment. If the service is initialized from the BS, the request will be passed to the scheduler. After the bandwidth broker allocates additional bandwidth for the new service, the BS will inform the user about the new bandwidth allocation and the transmission for the traffic of the new service will be guaranteed. In order to do so, a process for collecting the request information and service grant is depicted in Fig. 4. In a time frame (TF), all the requests are collected to a so-called request matrix ( $\mathbf{Y}$ ). This matrix is updated periodically every time frame due to the new incoming requests and finishing services. The granted matrix ( $\mathbf{X}$ ), which specifies the granted services, is found based on the available resource and the matrix  $\mathbf{Y}$ . For the services that are not guaranteed or do not have constraints on QoS parameters, e.g. file transmission, their access network can be organized by the scheduler as the best effort traffic type. A set of definitions for the four service classes as well as the bounds of corresponding parameters supported by the BPLC access are defined in [1] for the OPERA system.

Let us consider a cell in the multiple cells structure, which has a specific transmission capacity to share the transmissions of its devices. In this cell, the BS collects information of the transmission rates in the physical layer via the channel measurement procedure (e.g. see in [1]). This procedure is triggered frequently in order to obtain actual knowledge about the power line channel quality. The transmission data rates of the connections can be reported to the BS to generate the entire knowledge of the logical connections.

The use of repeaters, both a time division repeater and a frequency division repeater to extend the coverage of a PLC cell is also proposed in [1][2]. In this work, we consider the time division repeater and thus the resource that we consider is the duration of the transmission of each granted service in every time frame. Furthermore, because we limit the cell access time by the duration of the time frame (TF), we consider the end-to-end throughput as the main QoS parameter that the bandwidth broker has select for each user,

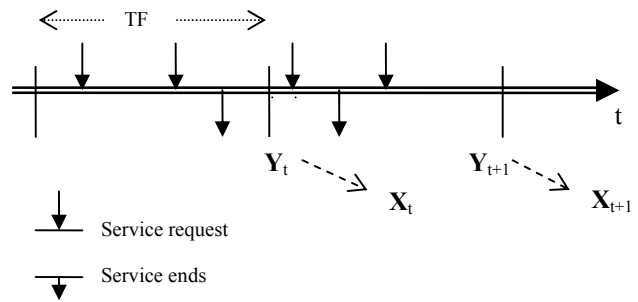


Fig. 3. Collection for Service Requirements

based on their requirements. The end-to-end throughput is directly proportional to the duration of transmission time in every time frame.

The calculation for the effective data rate is given in [10] and restated here for convenience. When a transmission from the BS to a user requires one or several repeaters, the transmission duration will be longer than a direct transmission. Due to the effect of necessary data repetition, we use the so-called effective data rate ( $ES_{U_i}$ ) for a connection between the BS and the user  $U_i$ .  $ES_{U_i}$  is defined as the ratio between the amount of data ( $L$ ) to be transmitted and the transmission time from the BS, through the connected repeaters, and to the user  $U_i$ . We investigate for the worst case, where only transmission in a link is allowed in an instant of time due to possible interferences. Therefore, the duration  $T$  for transmission the data  $L$  is the sum of all the durations over the transmission path. If the transmission path is concatenated from  $n$  links, each link  $l_i$  ( $i \in [1, n]$ ) has the physical bit-rate  $S_{l_i}$ , the effective data rate is

$$ES_{U_i} = \frac{L}{T} = \frac{1}{\sum_{i=1}^n \frac{1}{S_{l_i}}} \quad (1)$$

Utilizing the effective speed calculation, the network with several repeater levels can be converted to the network with only direct connections between a BS and users, as depicted in Fig. 4. Based on the knowledge of the connections to its users, the bandwidth broker in the BS divides the available resource to fulfill the requirements for different services from different users. In the TDMA system, the bandwidth assigned for a

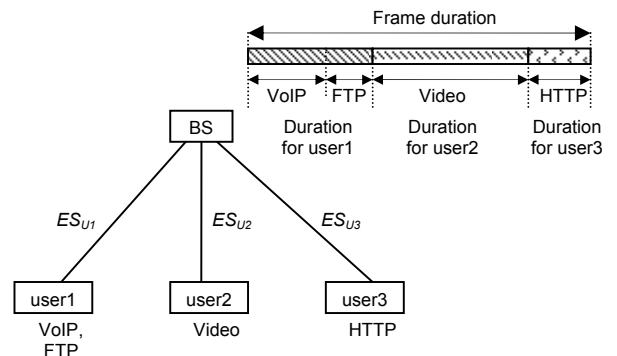


Fig. 4. Time slot allocation in a Time Frame

service is calculated as a ratio of the given time duration ( $T_{ij}$ ) per the frame duration ( $T^F$ ) and multiplied with the effective data rate from the BS to that user  $i$  ( $ES_{U_i}$ )

$$\beta_{ij} = ES_{U_i} \cdot \frac{T_{ij}}{T^F} \quad (2)$$

One example of resource allocation is presented in Fig. 4 in which the resource is the access duration (proportional to the bandwidth). The transmission duration can be allocated firstly to the user1 and the user2 that have VoIP and Video services which require a fixed amount of bandwidth. The rest of the transmission duration in the frame is then allocated to the FTP and HTTP services in user1 and user3 which are still acceptable in the case of lower bandwidth allocations.

## B. Objectives and Problem Formulation

### 1) Benefit

The benefit of a sharing solution is defined based on the “goodness” of the solution. It is calculated according to the benefit each user gets for his individual service assignment. E.g. a user gets higher benefit from a granted VoIP connection than the benefit from a data connection. Let’s assume that the utility of bandwidth granted to a service is the benefit of the service. We consider a BPLC system with a base station and  $N$  users, from  $U_1$  to  $U_N$ . Each can provide  $S$  service classes; from  $S_1$  to  $S_S$ . Table I shows an example of the resource requirement by different services with corresponding benefit of each service  $b_j$ . In the analysis section, the resource unit is normalized to simplify the calculation.

We define the request matrix and the granted matrix:

- Request matrix  $\mathbf{Y}=\{y_{ij}\}$ , where  $y_{ij}$  is a number of requests for a service  $j$  from a user  $i$  ( $0 \leq y_{ij}, y_{ij} \in \{\mathbb{N}\}$ )
- Granted matrix  $\mathbf{X}=\{x_{ij}\}$ ,  $x_{ij}$  is a number of granted requests of service  $j$  to user  $i$  ( $0 \leq x_{ij} \leq y_{ij}, x_{ij} \in \{\mathbb{N}\}$ )

Fig. 5 shows an example of a request matrix and a consequential granted matrix. Each element in the granted

TABLE I. SERVICES AND RESOURCE REQUIREMENTS

| Service Class | Throughput | Benefit $b_j$ | Example                  |
|---------------|------------|---------------|--------------------------|
| $S_1$         | 64kbps     | 8             | VoIP                     |
| $S_2$         | 128kbps    | 4             | Video, Game              |
| $S_3$         | 32kbps     | 2             | HTTP                     |
| $S_4$         | 1kbps      | 1             | Email, data low priority |

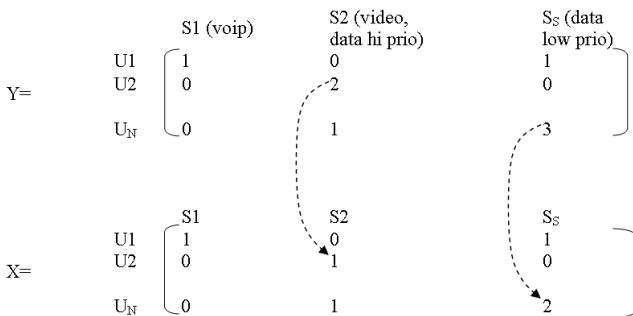


Fig. 5. Request matrix and granted matrix

matrix is found regarding the corresponding number of requests in the request matrix, as highlighted by the dashed-arrow lines.

To support multiple VPNs, the BS has to maintain a table describing the association of the users to the corresponding VPN, called VPN table:  $\mathbf{V}=\{v_{ik}\}$ , where  $v_{ik}=1$  if user  $i$  is associated to the VPN  $k$ ;  $v_{ik}=0$  otherwise. If there are  $K$  VPNs embedded inside this network,  $k \in [1;K]$ . VPN  $k$  has  $N_k = \sum_{i=1}^N v_{ik}$  users.

Let the benefit of a solution for all granted services for user  $U_i$  be  $B_{U_i}$ , it is the sum of the all granted services to this user:

$$B_{U_i} = \sum_{j=1}^S (b_j \cdot x_{ij}) \quad (3)$$

Considering the VPN  $k$ , the benefit of this VPN is the sum of all the benefits of it users:

$$B_{V_k} = \sum_{i=1}^N (B_{U_i} \cdot v_{ik}) = \sum_{i=1}^N \sum_{j=1}^S (b_j \cdot x_{ij} \cdot v_{ik}) \quad (4)$$

From the VPN provider’s point of view, the total benefit from all VPN is important

$$B = \sum_{k=1}^K B_{V_k} \quad (5)$$

Substitute (4) to (5) and do some simplifications with the notice that  $\sum_{k=1}^K \sum_{i=1}^N v_{ik} = N$  and  $v_{ik} \in \{0,1\}$ , we achieve

$$B = \sum_{i=1}^N \sum_{j=1}^S (b_j \cdot x_{ij}) \quad (6)$$

### 2) Intra-VPN Fairness and inter-VPN Fairness

When we only consider to maximize the total benefit, we may achieve the results where some users who require high priority services consume all the bandwidth. Thus, it is unfair for the rest of users. To avoid this situation, we use the idea presented in [6] to keep the fairness between users inside a VPN (called intra-VPN fairness) and the fairness between VPNs (called inter-VPN fairness). For evaluation, we derive the idea from the calculation for Jain’s fairness-index [11] to calculate our fairness-index definition based on the benefit of the users. Let  $r_k$  be the weight of the VPN  $k$ .  $r_k$  is normally specified by the VPN provider based on the VPN configuration, e.g. proportional to contracted line rate. Since we try to keep the ratio  $B_{V_k}/r_k$  uniformly for all VPNs, the inter-VPN fairness index is calculated by

$$FV = \frac{\left( \sum_{k=1}^K \frac{B_{V_k}}{r_k} \right)^2}{K \cdot \sum_{k=1}^K \left( \frac{B_{V_k}}{r_k} \right)^2} \quad (7)$$

Similarly, the intra-VPN fairness index inside the VPN  $k$  ( $FI_k$ ) is introduced to keep the benefit of the user in the VPN uniformly. We calculate the average of the inter-VPN fairness for all the VPNs in the network as

$$FI = \frac{1}{K} \sum_{k=1}^K FI_k = \frac{1}{K} \sum_{k=1}^K \frac{\left( \sum_{i=1}^N B_{Ui} \cdot v_{ik} \right)^2}{N_k \cdot \sum_{i=1}^N (B_{Ui} \cdot v_{ik})^2} \quad (8)$$

Both  $FV$  and  $FI$  take values between 0 and 1. The value of  $FV$  is 1 if  $B_{V_k}/r_k$  are perfectly equally distributed and becomes less than 1 when deviating from this situation. The value of  $FI_k$  is 1 if all benefits of users belonging to the same VPN  $k$  are the same and less than 1 otherwise.

In order to satisfy the QoS requirement for a service  $j$  from user  $U_i$ , we assume that a resource  $R_{ij}$  is necessary. When we consider the transmission duration is the resource ( $R_{ij}=T_{ij}$ ), each user requires a different amount of resource for satisfying the same service because of the different effective data rate between users and the BS. The resource or the transmission duration necessary to be allocated for this service is calculated from equation (2)

$$R_{ij} = T_{ij} = T^F \frac{\beta_{ij}}{ES_{U_i}} \quad (9)$$

For the whole network, the total allocated resource  $R$  to all users must be smaller or equal to the total available resource in the system ( $R_{max}$ ). Therefore, the condition of the resource allocation is

$$R = \sum_{i=1}^N R_{U_i} = \sum_{i=1}^N \sum_{j=1}^S (R_{ij} \cdot x_{ij}) \leq R_{Max} \quad (10)$$

where  $R_{U_i}$  is the resource allocated to user  $U_i$ .

Now, the resource sharing strategy can be formulated as an optimization problem with three objectives:

Find a granted matrix  $X$  from the request matrix  $Y$  in order to

- Maximize: The overall benefit  $B$  in (5),
- The inter-VPN fairness  $FV$  in (7)
- The intra-VPN fairness  $FI$  in (8)

such that:

$$0 \leq x_{ij} \leq y_{ij} \text{ and satisfying the limit resource condition in equation (10)}$$

#### IV. THE SCHEDULING SOLUTIONS

We apply a classical method to solve the multi objectives problem by aggregating the entire objectives into a general single objective function. Since the range of the value of  $B$  is unknown, it is difficult to build the common objective utilizing a linear scaling from three objectives [12]. In this problem, we know that both  $FV$  and  $FI$  are between 0 and 1. All the objectives have to be maximized, therefore we define the single objective is to maximize the so-called ‘‘fair-benefit’’:  $BFF = B \cdot FV \cdot FI$ . Before presenting the heuristic algorithm to solve the aforementioned optimization problem, the round robin scheduler and a so-called benefit based selection algorithm are described below.

##### A. Round Robin Scheduler (RRS)

Utilizing the round robin scheduler (RRS), the time frame, as resource, is divided into small portions for each user

depending on the weight of the associated ISP. Let the VPN containing user  $U_i$  be  $v_{U_i}$ , each user is reserved a resource for its transmissions equal to

$$R_{U_i} = \frac{R_{Max} \cdot r_{v_{U_i}}}{\sum_{k=1}^K (r_k \cdot N_k)} \quad (11)$$

In every time frame, the scheduler gets data from the queues of each user until it fulfills the reserved transmission resource or there is no more data to be transmitted. The scheduler delivers the resource to the services requested by a user depends only on the number of services, therefore, the time complexity of this method is product of the number of users and the number of resources  $O(N \cdot S)$

##### B. Benefit based Selection Algorithm (BSA)

The benefit based selection algorithm (BSA) is proposed based on the benefit achieved when consuming an amount of resource. Let  $\Delta BFF_{ij}^+$  be an additional fair-benefit gained by assigning resource for service  $j$  to the user  $U_i$ , which consumes resource  $R_{ij}$ . This algorithm contains the following steps

- Step 1: From the current capacity assignment (first time is empty), calculate  $\Delta BFF_{ij}^+ / R_{ij}$  for all possible assignments for all users.
- Step 2: Assign resource for the request which achieves the max of  $\Delta BFF_{ij}^+ / R_{ij}$
- Step 3: Repeat the step 1 until it meets one of the following conditions:
  - resources are allocated to all requests or
  - out of available resource

For the search, the total number of requirements is  $d = \sum_{i=1}^N \sum_{j=1}^S y_{ij}$ . In the worst case, the algorithm has to run for  $d+(d-1) + \dots + 2 + 1 = d(d+1)/2$  times to grant resource for all requests. Eliminating the time for comparisons, the time complexity of this method is  $O(d(d+1)/2)$ .

##### C. Heuristic Algorithm (HA)

We propose a simple heuristic algorithm to rearrange the resource between different service requests. In the first step, the algorithm finds a feasible solution by means of the calculation in the RRS method. After that, in order to increase the available bandwidth for doing further bandwidth allocation, the bandwidth is taken from a random service in a random user when the available bandwidth is smaller than  $R_{dg}$ . The procedure is repeated for a given number of iterations or the calculation time is greater than the given limitation. In summary, the heuristic algorithm comprises with the following steps:

- Step 1: Distribute the available resource to users according to the RRS calculation to find a feasible solution.
- Step 2: Downgrade the solution (remove one or some services)



- Do one or some random downgrades by removing one or some random services from a random user (the allocated services) when the rest of resource is smaller than a given  $R_{dg}$
- **Step 3:** Upgrade the solution (add service)
  - Calculate  $\Delta BFF_{ij}^+ / R_{ij}$  for all the possible upgrades
  - Compare  $\Delta BFF_{ij}^+ / R_{ij}$  and do upgrade by adding service  $j$  to user  $i$  with the highest found value
- **Step 4:** Repeat the step 2 and 3 until the stop criterion is met

The calculation time can be predefined as a stop criterion. Therefore, the calculation for the time complexity is not necessary for this heuristic algorithm.

## V. ANALYSIS OF THE SCHEDULING STRATEGIES

In order to calculate numerical results, we normalize the available resource in a network according to the number of users and traffic demands. For simplicity, we assume that the amount of resource allocated for each service is the same for all users and we use the BPLC network model presented in [10]. Each user  $U_i$  requests for  $y_{ij}$  instant sessions of service type  $S_j$ . The number of requests for a service from a user is chosen uniformly at random from the interval  $[0,2]$ . It means that each user can request for maximum two sessions of the same service at an instant of time. Each user can choose services in four classes:  $S_1, S_2, S_3, S_4$ . The services  $S_1, S_2, S_3, S_4$  request 1, 2, 1, 0.01 normalized resource unit and achieve 8, 4, 2, 1 unit of benefit, respectively. We run the strategies for

three network scenarios named  $NW1, NW2$ , and  $NW3$ . There are 32, 64, and 128 users in these networks, respectively. The number of available resources is twice time the number of users, i.e. 64, 128, 256 for the three scenarios. Each network contains of two VPNs (VPN1 and VPN2), each provides services to the half number of users. The weights of the corresponding ISPs are  $r_1=1$  and  $r_2=2$ .

We propose to start the QoS guarantee inside 10 times of the round trip time after the request is made, i.e. 300ms for the BPLC network. For the calculation by the computer which has a CPU running at 2GHz and 256MB of RAM, the RRS and the BSA get results in a short time (significantly shorter than 300ms). The HA algorithm can be executed with 100 iterations (conducted by the step 2 and step 3) within a duration shorter than 300ms. Each network scenario and with an algorithm is run for many times to get the average results for different random traffic requirements. The achieved confidence interval is smaller than 5% of the mean values when calculated with the confidence probability equal to 0.95. Therefore the confidence interval is not shown in the graphs. The results are presented in the bars for the RRS, the BSA, and the HA from the left to the right in all the following graphs.

### A. The Inter-VPN Fairness (FV)

The comparisons of the inter-VPN fairness in case of the three given networks and with three scheduling strategies are presented in Fig. 6. The RRS achieves higher  $FV$  than the BSA, because the resource in RRS is allocated based on the weight of VPNs. The HA produces the highest  $FV$  in the three given network scenarios.

### B. The Intra-VPN Fairness (FI)

Since the number of service requests is different from users, the RRS creates unfairness between users inside a VPN. The  $FI$  achieved when using RRS is relatively low, under 0.83. The BSA tries to achieve a high benefit so it may allocate great amount of resource for the high priority services and leave the other services without granted resource. The BSA therefore can not provide good  $FI$  for the users. However, the HA can release the resources from the high priority services and allocates them to the lower one, making balance between users. According to the results presented in Fig. 7, the HA

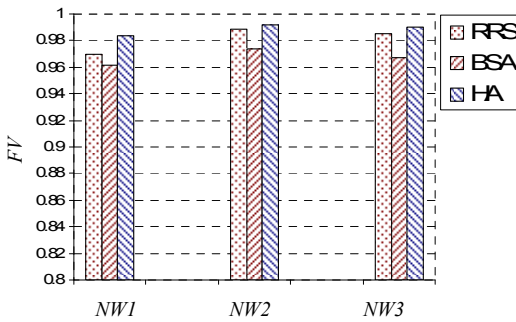


Fig. 6. Inter-VPN fairness comparisons

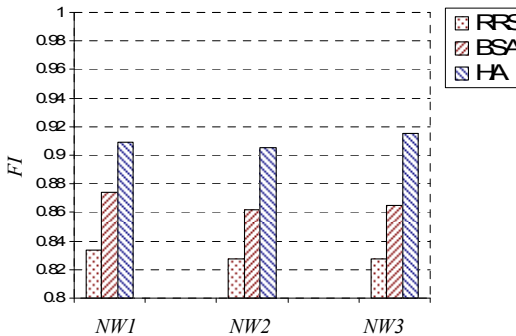


Fig. 7. Intra-VPN fairness comparisons

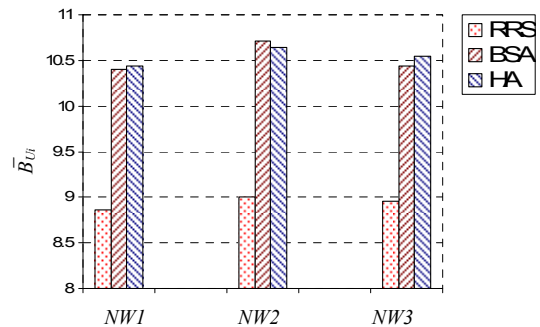


Fig. 8. Average benefit comparisons

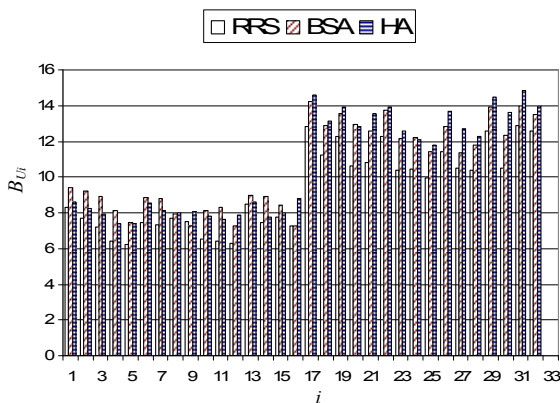


Fig. 9. Benefit of individual user

achieves  $FI$  greater than 0.9 for all three networks. It is also the highest values comparing to the results from the RSS and the BSA.

### C. The Average Benefit ( $\bar{B}_{U_i}$ )

The average benefit is evaluated to demonstrate the efficiency of the resource utilization (Fig. 8). The RSS achieves the lowest values comparing with the other methods. The RSA and the HA achieve almost the same average benefit because they both try to maximize  $B$ . The results from the HA is slightly higher than the results from RSA in case of  $NW1$  and  $NW3$  and a little lower in the case of  $NW2$ .

To demonstrate the effects of the weights of VPNs, the benefit is presented for all users individually for the network with 32 users ( $NW1$ ) in Fig. 9. The users from 1 to 16 associated to the VPN1 and have more than half of the benefits of the users from 17 to 32 that belong to VPN2. This happens because the VPN2 has the weight equal to two times the weight of the VPN1 ( $r_1=1, r_2=2$ ). The HA and the RRS try to differentiate between the users based on the weights of users' VPNs while the RSA allocates fairly resources to the users belonging to the lower-weight VPN.

## VI. CONCLUSION

We proposed scheduling strategies to allocate the limited resource (transmission capacity) to the users in different VPNs over a BPLC network. The solution is evaluated by the overall benefit and the fairness between users in the same VPN as well as the fairness between VPNs. The overall benefit is calculated based on the benefit of the granted bandwidth to a particular service. The inter-VPN fairness and intra-VPN fairness are calculated based on the benefit achieved by the users. The solution of the resource sharing problem is solved based on the BPLC system parameters provided by the OPERA specification. The limited time frame duration in the OPERA BPLC system is divided into small portions for serving the granted services. While doing so, a base station has to maintain the available resource while satisfying the requirements from multiple users. The problem is formulated as an optimization problem and solved by the RRS, the BSA, and the heuristic approach. The weight of the VPN is taken

into account.

Only trying to maximize the fairness between all users in the case one has low data rate is disadvantageous because the overall system performance will be strongly decreased. This happens when the scheduler has to allocate very long time slot to satisfy the QoS requirement in a very low data rate connection and leaves only short time slots for the better connections. The proposed scheduling approach is a trade-off solution between fairness and the maximum of the benefit of the allocated transmission rates. When utilizing the three scheduling strategies, the RRS and the HA outperform the BSA in terms of inter-VPN fairness. The BSA and the HA obtain higher benefit than the RRS while maintaining the good intra-VPN fairness.

In reality, the variation of the request matrix happens not so often, depending on the type of request services. Therefore, the solution for a scheduling scheme can be found based on the number of changes of connection requests instead of the whole request matrix. We will consider this characteristic in our future works. Sharing the bandwidth between VPNs in the case of congestion in the backbone network will be also investigated as well.

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