On the Feasibility of Service Composition in a Long-Reach PON Backhaul

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***Abstract*—As network architectures are continuously evolving and being integrated with new technologies to meet the demands and requirements of future applications, many new possibilities and challenges emerge. Additionally, the evolution of user devices has brought other new possibilities, where devices in the same vicinity can offer and exchange services with each other. A vision that has led to developing various service discovery and composition models that aim to satisfy different constraints while ensuring a better quality of service.**

In this paper, we consider service discovery and composition in an optical access network, serving as a backhaul for a wireless front-haul, and examine how it can be greatly affected by the underlying bandwidth allocation scheme. We compare the performances of centralized and decentralized-based service compositions and study their side effects on upstream traffic. Numerical results demonstrate how decentralized allocation can be much better suited for supporting such service models and associated traffic in terms of both service delays and side effects on regular upstream traffic.

***Keywords*—Edge computing, Ethernet passive optical network (EPON), fiber-wireless (FiWi), fog computing, long-reach passive optical networks (LR-PONs), offloading, service composition**

I. Introduction

The evolution and widespread of mobile and IoT devices has led to a new era, where everything is now being reshaped to fit arising trends and better serve tomorrow's requirements. On one hand, network infrastructures have been constantly evolving and going through many reformations to better accommodate the exponential increase in user traffic and to meet application requirements with improved service quality. On the other hand, breakthroughs in the capabilities of edge and mobile devices, in terms of memory, computational power, and storage capacity, had led to broad possibilities of how services can be provided.

As edge devices are becoming smarter and more powerful, with a wider range of functionalities, fog and edge computing paradigms continue to spread, addressing the new demanding application requirements. These new paradigms enable the storage and computational resources of the cloud to be extended all the way to the edge of the network [1]. Not only does this enable resource-constrained devices to offload more tasks with strict latency or location-aware requirements, but it also allows much of their generated traffic to be processed at the network edge instead of being carried to the cloud [2].

The advances made in end devices themselves and their ample widespread has also introduced new possibilities, where devices in the same vicinity can start exchanging services. This new vision has led to developing various service discovery and service composition techniques, where individual services, in a service-oriented environment, can be looked up and properly combined to solve more complex tasks [3]. While the environment can be anything from a mobile network to a deep space research station, the service itself can be any accessible software component, hardware resource, or data segment that can be offered to other devices [4]. This concept brings many potential assets for a wide range of applications and scenarios such as image processing, sharing GPS/internet data, crowd computing, social networking, or aggregating and integrating sensor data to discover meaningful trends such as current weather or traffic conditions [5].

The ubiquity of mobile devices and their evolution into significant service computing platforms has thus drawn much attention in the literature. Some studies focused on the devices' mobility aspect and how it may affect the feasibility of service composition [6]–[8], whereas other studies considered it from an energy consumption perspective [9]. In this paper, we study the feasibility of service composition in optical access backhauls, which are widely believed to play a vital role in tomorrow's infrastructures given their high offered capacities and their cost-effective deployment and operation [10]–[12]. Many architectures have already proposed integrating them with fog computing in order to better serve wireless front-hauls [13]–[15]. Still, the effects of offloading traffic on the network performance as well as the feasibility of service composition itself, in optical access networks, have not yet been addressed. Moreover, many studies only focused on achieving performance gains in the wireless front-end with little regard to the backhaul and its possible bottlenecks [16].

In this paper, we investigate the performance of offloading services and retrieving results, in a *long-reach passive optical network* (LR-PON), when the underlying dynamic bandwidth allocation is either centralized or decentralized. We also study the effect of carrying this new type of traffic on regular traffic. In Section II, we start by formulating our service discovery and composition problem. In Section III, we then demonstrate how

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service composition can be accomplished in each allocation paradigm. In Section IV, we present numerical results, whereas Section V concludes the study.

II. Problem Formulation and Assumptions

In this section, we first describe the network architecture of the *fiber-wireless* (FiWi) network under consideration before laying out the service composition problem and its relevant assumptions.

A. Network Architecture

LR-PONs were first introduced around a decade ago as a highly cost-effective broadband solution since they can extend the coverages of traditional PONs up to a 100km or more. This allows combining access and metro networks into a single integrated network as well as connecting more users, thereby saving huge operational and capital costs [17]. Fig. 1 illustrates one of the most common LR-PON architectures, in which each access zone is served by dedicated upstream and downstream wavelengths that enable the *optical network units* (ONUs) to communicate with their associated *optical line terminal* (OLT). The ONUs can then be connected to access points or base stations that enable them to serve wireless devices or they can alternatively be connected to wired subscribers [13].

Because the network in the upstream direction forms a multipoint-to-point network, where multiple ONUs transmit toward the OLT through a shared medium, some form of channel arbitration is required to coordinate the ONUs' transmissions and avoid data collisions. For that purpose, *time-division multiple access* (TDMA) has been adopted in most PON standards, where each ONU is periodically allocated a timeslot for transmission. This upstream bandwidth allocation can then either be centralized or decentralized.

B. Edge/Fog Computational and Storage Resources

There have been many architectures in the literature that propose connecting cloudlets or micro-datacenters to optical access networks in various ways [13]–[15]. Alternatively, some studies proposed forming a local cloud from the resources of the optical network itself [18]. Besides being relatively close to each other, the computing and storage resources of the ONUs together exceed that of the OLT by more than eightfold. This led to the idea of making these ample resources accessible to their connected devices.

In this paper, we consider a LR-PON with N ONUs capable of receiving service requests from their connected devices. To formulate our service composition problem, we assume the following with regard to the available computational resources:

- each ONU is capable of running some computational tasks besides its main functions as well as using part of its memory for storage purposes,
- ONUs in the same network are identical (homogenous computing resources),
- an ONU can compose a service from its own offered services or from those currently offered by its connected devices with acceptable battery levels.

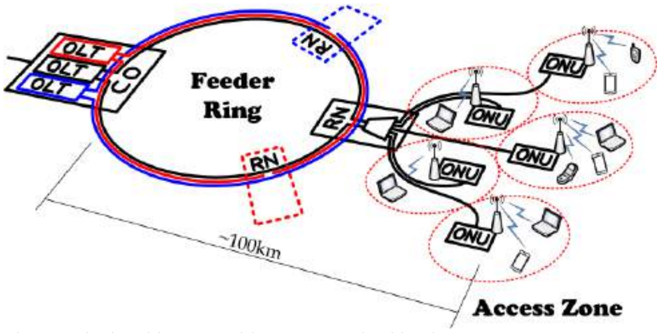

Fig. 1. FiWi architecture with a LR-PON backhaul.

We then assume the following assumptions for a given requested service (offloaded task):

- a task T is requested by a user device connected to an ONU which we call the client ONU or ONU$_c$,
- if the request is accepted, task T is to be carried out using some offloaded data and an associated set of operations that are altogether R bytes in size,
- R is fragmented into Ethernet packets that add up to D bytes in size (including overheads),
- task T may be a composition of multiple services that can be broken into S subtasks or services, which may be composed and run on multiple devices,
- either the OLT (centralized case) or the client's node ONU$_c$ (decentralized case) will be responsible for finding an ONU with enough resources to manage the service composition based on a utility function U,
- the elected composition manager ONU, which we call ONU$_m$, will be responsible for composing the service, collecting the final result (which is E bytes in size), and sending it back to ONU$_c$,

Finally, in our work, we assume that regular upstream traffic is always given higher priority than service traffic. In other words, only unused bandwidth is used for offloading and exchanging edge traffic.

C. Offloading and Service Composition

Before a device can offload a task to the network, the device must first construct a requirement list that specifies the services required and its corresponding QoS requirements for each service. The device then embeds this list into a service request message that it sends to the ONU to which it is connected. Once the ONU receives this service request, four phases are then required to compose the requested service, assuming that the client's ONU does not currently have the resources to do the service composition itself:

1) Composition Manager Selection Phase

Using the cyclic updates collected from other ONUs, either the OLT (in the centralized case) or ONU$_c$ (in the decentralized case) elects an ONU that will manage the service composition. The elected ONU (ONU$_m$) will be the one that currently has the highest available computational resources, offers the requested services, and meets the QoS requirements of these services.

Similar to [4], this ONU election can be based on a utility function U, which can be expressed as;

$$U(ONU_i) = \alpha N(ONU_i) + \beta M(ONU_i) + \gamma Q(ONU_i) \quad (1)$$

where N and M are the numbers of services currently being offered by the i^{th} ONU itself and by the devices connected to it, respectively, whereas Q is a metric that reflects the similarity between the services offered and those requested. α, β, and γ are corresponding weights that may be used to prioritize one utility parameter over the others. After ONU_m is successfully elected, the task has to be passed on to it. ONU_c can then accept the service request from the device, allowing it to offload any task data, before forwarding it to ONU_m.

2) Service Discovery Phase

In this phase, the selected composition manager performs the service discovery process, in which it investigates all the services offered by its connected devices as well as by itself. The manager then selects the best available services that are to be integrated together to provide the required service. The service discovery phase is thus composed of two main steps: forming a candidate list and ranking each candidate.

The first step requires ONU_m to have a list of the services currently being offered by the devices in its vicinity along with their corresponding QoS metrics. This list may be already available to ONU_m through a locally cached description, which can easily be gathered from its connected devices' periodic updates. Moreover, the services must be represented by their storage or computational capabilities as well as their particular service type (i.e., 100MB memory storage availability or 1GHz processing speed).

The second step, however, must use some information from the service request message to compute the rankings of the available services using a ranking function R, such as;

$$R(s_j) = w_c . w_r . sim(s_j, \boldsymbol{S_r}) \quad (2)$$

where w_c and w_r are weights that reflect the availability of a candidate service and the priority of a required service, respectively, whereas $sim(s_j, \boldsymbol{S_r})$ is a similarity function that matches between a service offered s_j and a set of requested services $\boldsymbol{S_r}$ of similar nature. If multiple instances of the same service exist, the weight w_c can be used to give preference to one over the others based on some metric (e.g., distance: the nearest one or the one having the least number of hops).

3) Service Integration and Execution Phase

In this phase, ONU_m coordinates the execution of the selected services in the order specified by the service request message. It also ensures the transfer of intermediate results from one service to another when necessary. Execution can therefore occur in a distributed manner, where partial results received from a service (executed on one device) can be transferred to the following service (executed on another).

4) Result Collection Phase

Finally, if one or more of the services produces a result, the final output must be sent back to the device where the service request originated. This means that results first need to be gathered by ONU_m and then sent back to ONU_c, to which the device is connected.

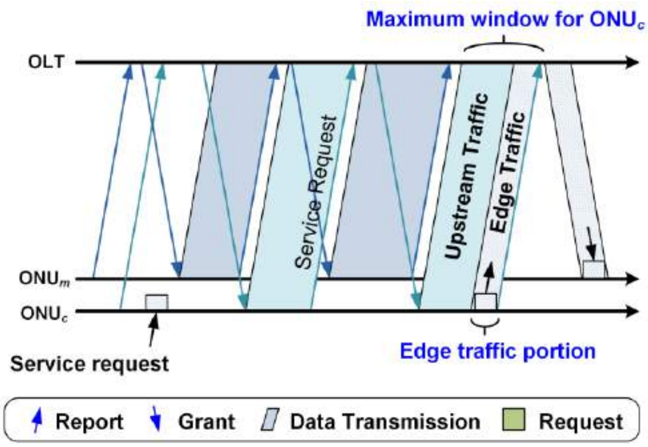

Fig. 2. Centralized-based service composition offloading.

Of these four mentioned phases, the second two phases, in which the service has already been transferred to ONU_m, are not dependent on the underlying bandwidth allocation, in contrast to the first and last phases, in which the data is transferred back and forth between ONU_c and ONU_m. In the next section, we study how these phases can be carried out in each bandwidth allocation scheme.

III. SERVICE COMPOSITION IN LR-PONS

The exchanging of service requests and offloaded traffic is different in each allocation scheme. In this section, we examine how it can be carried out with centralized and decentralized bandwidth allocation paradigms.

A. Centralized DBA – Polling

Centralized *dynamic bandwidth allocation* (DBA) has been widely considered in the literature [19]–[21], in which, the OLT arbitrates the ONUs' bandwidth allocation. As illustrated in Fig. 2, the OLT basically polls each ONU with a grant message, giving it a window to transmit according to a previously received report message that reflects the ONU's queue status. ONUs, on the other hand, do not need to monitor the network state nor exchange any information, which makes their design relatively simple.

With no direct inter-ONU communications in centralized allocation, ONU_c will have to forward the service request to the OLT, which would then be responsible for selecting the composition manager (ONU_m) based on information gathered from its most recently received reports. This, of course, would require ONUs to continuously append the availability of their resources and offered services in all their outgoing reports, something that is not found in a conventional allocation algorithm. Once the OLT elects a composition manager with enough resources to carry out the task, it will accept the service request and start granting ONU_c more upstream bandwidth up to the maximum allowable by its service level agreement. Using this additionally allocated bandwidth, ONU_c will start uploading the relevant task data, as illustrated in Fig. 2. This can last for more than one cycle depending on the ONU's current upstream load and the size of the offloaded data.

After receiving the offloaded data, the OLT forwards this data to ONU_m along with the original service request and its requirement list. ONU_m then carries out the service composition, integration, and execution phases, before sending back the results to ONU_c. This again is done by sending them first to the OLT using the excess bandwidth granted by the OLT in its following transmission windows.

B. Decentralized DBA

Because polling forms the basis of centralized DBA, the performance of such allocation greatly depends on the *round-trip times* (RTTs) imposed on the bandwidth negotiation messages exchanged between the ONUs and the faraway OLT. While this does not pose challenges in traditional PONs with 10-20km spans, RTTs become more severe in LR-PONs causing the DBA performance to considerably degrade [19]. Decentralized bandwidth allocation has therefore been proposed as an alternative for LR-PONs, where the ONUs themselves manage the upstream media access instead of having to periodically report their buffer status to the remote OLT and then wait for grants to transmit. However, for the ONUs to successfully manage the upstream media access, they need to communicate together; something that was not needed nor available in the original network design.

One possible way of achieving inter-ONU communications is to place a *fiber Bragg grating* (FBG) near the remote node which selectively reflects back a single wavelength to the ONUs facilitating an *out-of-band* (OOB) multipoint-to-multipoint network. This was shown in [22] to be a viable option for inter-ONU networking and was also used in [23] as the basis for a decentralized media access scheme.

In [23], this inter-ONU communications technique was used to enable the ONUs to take turns transmitting on the upstream wavelength by announcing to each other the durations of their transmissions. This was done by making each ONU send a very short time-stamped frame (a tag) at the beginning of its transmission, announcing how many bytes it intends to transmit without exceeding a certain maximum. This maximum was set by the OLT during an initialization phase according to the ONU's service level agreements. Chances of upstream inter-transmission gaps are then reduced since the time it takes the frame to reach the following ONU on the control channel will be during data transmission on the upstream channel. With no reports to the OLT, the delays in this decentralized scheme are fully independent of the RTTs. Instead, the delays depend on the distances between the ONUs and the reflective device.

In this work, we modify this OOB tagging scheme to allow edge data to be exchanged between ONUs on this additional channel during an offloading or a result retrieval phase. We propose to place a flag in the tag message, which, if toggled by an ONU, will indicate that this ONU needs to transmit edge traffic in the next cycle. As illustrated in Fig. 3, once this flag is toggled, the ONUs switch to another tagging scheme in the next cycle, where all the tags are immediately sent in the beginning of the cycle, thereby giving room for edge traffic to be exchanged. This tagging scheme continues to be used by all ONUs as long as one of them still has a toggled flag in its last

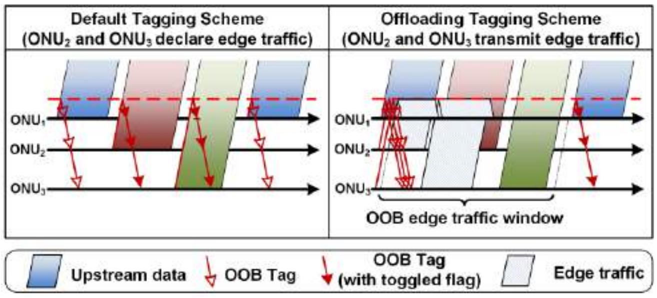

Fig. 3. Default decentralized tagging scheme and proposed offloading tagging scheme which is provoked when the edge traffic flag is toggled.

tag message. Additionally, the OOB edge window can be shared among multiple ONUs by simply dividing it equally among those ONUs which had their flag toggled in the previous cycle. Alternatively, the ONUs may share the length of their OOB transmissions along with the toggled flag for better OOB utilization and lower edge delays.

Because tags are exchanged in the beginning of the cycle (during the upstream transmission of the first ONU), ONUs cannot transmit more than what had already been announced in their tags. The ONUs may therefore choose to reserve the same transmission windows they used in the previous cycle, by announcing so in their outgoing tags, even though they may not have enough packets yet in their buffers to fully utilize these windows. This however gives each ONU the chance to accommodate some newly arriving packets between the time of sending its tag and the time it starts its upstream transmission.

Inter-ONU communications in the decentralized scheme enable the first and last service composition phases, discussed in Section II, to be carried out in a different manner from its centralized counterpart. Here, ONU_c will be responsible for electing the composition manager from the information received in the last $N-1$ tags. This means that all ONUs need to continuously append their computational status and offered services in any outgoing tag message similar to what is proposed to be done within centralized reports. Using this information, ONU_c directly selects ONU_m, without involving the OLT, and broadcasts this selection in its next outgoing tag. This particular tag will not only specify the selected node, but will also have its offloading flag toggled so that the ONU may directly start transferring the service data to ONU_m within the next cycle. Contrary to the centralized scenario, edge data here does not have to go through the OLT. Instead, it is directly broadcasted to all the ONUs on the OOB channel. Once the necessary input data reaches ONU_m, the second two phases can then take place similar to the centralized scenario.

After finishing the service integration and execution, ONU_m sends back its output to ONU_c again using the OOB channel in a similar manner as was done in the first phase.

IV. Numerical Results

In our study, we consider a 100km long-reach symmetric Ethernet PON consisting of an OLT and 16 ONUs. The ONUs are placed randomly in the last 5km of a 100km network span, assuming that the FBG is located 95km away from the OLT. ONUs share an upstream wavelength of 1Gbps, whereas from

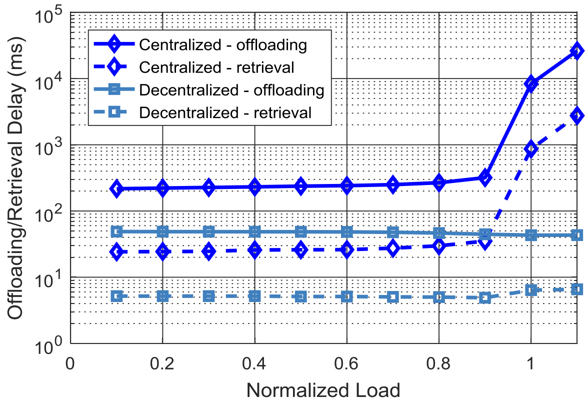

Fig. 4. Offloading and retrieval delays for a 5MB task with a 500KB result.

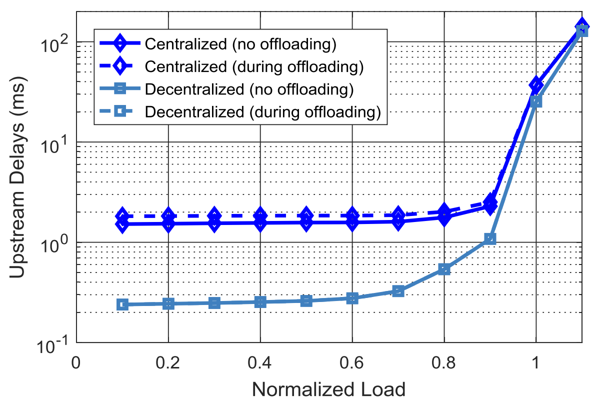

Fig. 6. Effect of service traffic on regular upstream traffic.

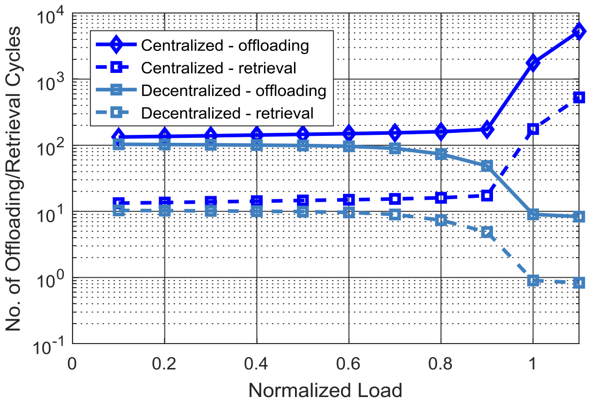

Fig. 5. Number of offloading and retrieval transmission cycles for a 5MB task with a 500KB result.

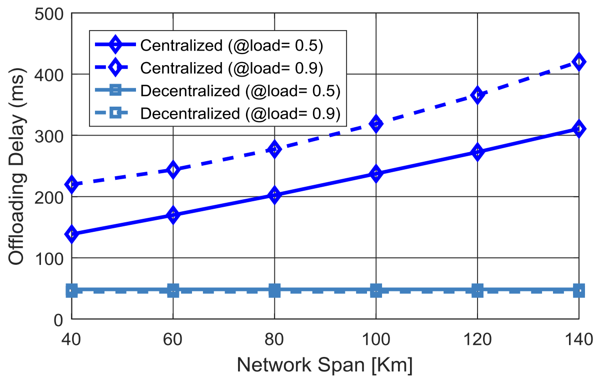

Fig. 7. Effect of network span on offloading delays.

the access side the end-users have an access rate of 100Mbps. Each ONU has a 10Mbytes buffer, whereas the traffic model used is self-similar Ethernet traffic, constructed from alternating on/off Pareto-distributed streams with a Hurst parameter of 0.8, similar to the traffic model used in [19], [23].

In order to compare the performances of the two schemes, the maximum cycle duration is set to 5ms for both schemes with 5µs inter-transmission guard intervals for both in-band and out-of-band traffic. For the proposed decentralized scheme, we set the OOB transmission rate to 1Gbps, through which ONUs also inform each other of their edge transmission sizes in their outgoing tags with toggled flags. During edge traffic exchange, ONUs reserve the same transmission windows they used in the last normal cycle.

A. *General Performance*

Fig. 4 illustrates the offloading and retrieval delays for a 5MB task having a 500KB result. It can be seen how, in centralized allocation, the delays increase with the increase of the upstream traffic load, especially at loads greater than 90%. This is because, as the network load increases, unused excess bandwidth in the ONUs transmission windows decreases. With normal upstream traffic having a higher priority, edge traffic would then take longer to transmit and would last for more cycles under heavy loads. This can also be seen in Fig. 5, which shows the number of cycles used to exchange edge traffic for both schemes. On the contrary, edge delays in the decentralized scenario seem to be unaffected as the load increases. In fact, the number of transmission cycles is shown to decrease with increasing the network load. This is because, as the cycle is extended more towards its maximum, a larger OOB edge transmission window is formed.

B. *Effect on Upstream Traffic Delays*

Fig. 6 shows how pre-transmission delays of regular upstream traffic are affected during an offloading phase. Injecting edge traffic on the upstream wavelength is shown to have a significant effect on centralized upstream traffic delays, but has no effect on decentralized delays. This is because injecting edge traffic extends the centralized polling cycle, by the additional excess bandwidth portion used for edge traffic, causing more delays for queued upstream traffic. On the other hand, exchanging edge traffic is implemented out-of-band in the decentralized scheme without causing any cycle extensions.

It is worth mentioning that the effects seen in Fig. 6 are only caused by a single ONU's offloading. The effects will therefore be exaggerated in the centralized scheme when multiple ONUs are concurrently offloading edge traffic to the

OLT. These effects, however, only last while there are ongoing edge traffic transmissions. The overall performance would, therefore, depend on how often the network has to deal with edge traffic as well as the amount of that traffic.

C. Effect of Extending Network Span on Service Delays

As was mentioned earlier, centralized allocation is greatly affected by extending the network span. Fig. 7 demonstrates a comparable effect on centralized service delays, where the performance of centralized-based offloading is ultimately degraded as the network span continues to extend. On the other hand, extending the feeder span shows to have no effects on the performance of decentralized-based offloading since the access span is kept constant at 5km.

V. Conclusions

In this paper, we investigated the feasibility of service composition in a long-reach optical access network serving as a backhaul for a wireless front-haul. We studied the delays experienced in offloading service traffic to the composition manager as well as those experienced in retrieving the composed service results. We also examined side effects of service composition traffic on regular upstream traffic.

Because decentralized-based service composition requires no OLT involvement, it has the potential of achieving much lower service delays. Decentralized-based service composition has also shown to have no side effects on regular upstream traffic. These advantages however come at the cost of placing additional transceivers within the ONUs and modifying the architecture to allow inter-ONU communications to take place. Moreover, ONUs themselves have to select the composition manager and may thus be relatively more computationally loaded than in a centralized-based scheme.

On the other hand, centralized schemes may still yet offer some benefits for service composition despite their long delays. For instance, the OLT can easily gain access to ONUs in other access zones to which it may choose to forward service requests instead. Centralized-based service composition may thus offer lower service rejection ratios as well as additional services only available in other access zones. This paper thus opens the door for further studies and calls attention toward a possible hybrid scheme that combines the potential benefits of both centralized and decentralized-based service compositions in these long-reach optical access networks.

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