A Generic End-to-end Distributed QoS Management Architecture and its Application to IP-DiffServ over a WDM Access Feeder Network

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Abstract

The growing widespread use of advanced multimedia and interactive real-time applications is setting forth new challenges such as end-to-end Quality-of-Service (QoS) and broadband Internet access. The high bandwidth needs are pushing fiber closer and closer to the home, and as such WDM (Wavelength Division Multiplexing) seems ideally suited to be used in the broadband access feeder network which interconnects the Internet core networks and the last mile networks.

In the HARMONICS project[1] (Hybrid Access Reconfigurable Multi-wavelength Optical Networks for IP-based Communication Services), a novel DWDM (Dense Wavelength Division Multiplexing) based optical access feeder network is investigated. This feeder network transports IP, guarantees QoS and can feed various last mile networks, stimulating the convergence of access networks. VDSL and Hiperlan/2 are studied within the project as last mile access networks.

To support end-to-end QoS, a distributed CORBA-based generic network management framework is being developed as part of the project. This paper will elaborate on the framework which is aligned with TINA, although adapted to be more consistent and applicable. End-to-end QoS is based on Differentiated Services (DiffServ) at layer 3, various QoS supporting technologies at layer 2 and QoS mappings between both layers.

Keywords

End-to-end QoS management, distributed management, DiffServ, CORBA, IP-over-WDM

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1 Introduction and Motivation

The massive growth of next generation multimedia and real-time applications is asking more and more from the networks such as end-to-end Quality-of-Service (QoS) and broadband Internet access. A variety of emerging advanced network technologies such as xDSL (Digital Subscriber Line) or wireless Hiperlan/2 tackle those issues for the last mile network. The high bandwidth needs are pushing fiber closer and closer to the home, and as such WDM (Wavelength Division Multiplexing), promising to provide the needed high bandwidth, seems ideally suited to be used in the broadband access feeder network which interconnects the Internet core networks and the last mile networks.

The HARMONICS (Hybrid Access Reconfigurable Multi-wavelength Optical Networks for IP-based Communication Services) project studies a DWDM based access feeder network carrying IPv4/IPv6 traffic directly over WDM with QoS guarantees. HARMONICS aims at stimulating the convergence of access networks by supporting a variety of last mile network technologies. Differentiated Services (DiffServ) is used as end-to-end QoS mechanism on Layer 3, supported on L2 by a new wavelength/time slot MAC protocol in the optical network and novel QoS mappings for the various last mile technologies.

Within the project, different scenarios and possible migration schemes are studied ranging from 64 Optical Node Units (ONUs), serving a total of 3200 VDSL subscribers, to 1024 ONUs for FTTH/B (Fibre-to-the-Home/Building). The considered line rates are 622 Mb/s upstream, and 1.2 Gb/s downstream for each channel and transceiver.

This article focuses on both the end-to-end QoS provisioning at layers 2 and 3 and the generic end-to-end QoS connection management framework. The novelty in the QoS provisioning is the mapping of DiffServ at L3 to WDM at L2, the new MAC protocol in the Optical Feeder Network (OFN) and the support for a variety of last mile technologies. DiffServ management at the other hand is a topic under widespread research, but the proposed approach is based on the deeply studied TINA principles [8], is CORBA based with support for RSVP and is especially focused on inter-domain and multi-technology management, problems which are not solved yet. Initialization and connection setup scenarios are described together with the IDL interfaces.

The remainder of this paper is structured as follows: Section 2 describes the HARMONICS network architecture in detail. Section 3 discusses how end-to-end QoS is achieved within HARMONICS, while Section 4 elaborates on the distributed QoS management architecture. Section 5 presents an overview of the Lab and Field Trial and finally Section 6 concludes this paper.

2 HARMONICS Network Architecture

The HARMONICS broadband access feeder network consists of two main parts, as shown in Figure 1: (i) the Optical Feeder Network (OFN) and (ii) the

Last Mile Network (LMN) which supports multiple access networks based on various technologies. Interconnection of the various parts is accomplished by IP routers. *HARMONICS Leaf Routers (LR)* connect last mile networks to the OFN, while a *HARMONICS Edge Router (ER)* connects the OFN to the core network (= IP backbones).

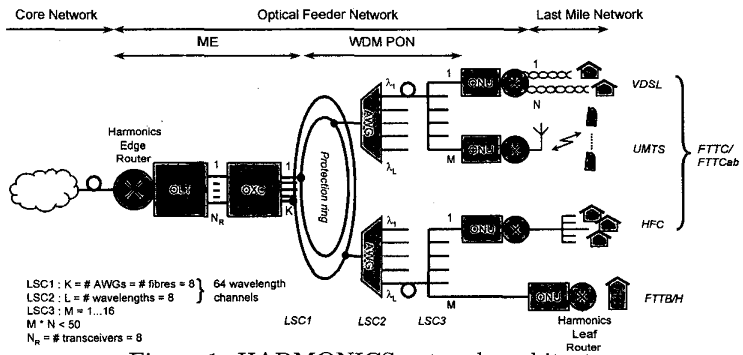

Figure 1: HARMONICS network architecture

The Optical Feeder Network (OFN) is basically an IP-over-WDM Network. From an IP point of view, the OFN is completely transparent – only the Edge Router at the core side and the Leaf Routers at the user side are visible. As such it provides Fiber-to-the-Curb (FTTC), Cabinet (FTTCab) and FTTH/B configurations.

At the optical layer, the PON provides the connectivity between the Edge and Leaf routers. It is composed of a tree-and-branch PON connecting an OLT to different ONUs. There is a dedicated Leaf Router for every ONU, while the OLT is connected to the sole Edge Router. The PON deploys different multiplexing schemes to provide sufficient bandwidth across an area with a 20 km radius [1].

The PON design in Figure 1 was selected after careful consideration of aspects such as power budget, component costs and compatibility with existing infrastructures. Space Division Multiplexing (SDM) is used at Local Splitting Center 1 (LSC 1) by using a separate fiber for each AWG (Arrayed Waveguide Grating), Wavelength Division Multiplexing at LSC 2 by AWGs, and Time Division Multiplexing (TDM) by power splitters at LSC 3. The system is preferably deployed with a single type of ONU capable of transmitting at any channel wavelength, rather than several types each capable of transmitting at a single channel wavelength.

Dynamic reconfigurability of network capacity is performed by the optical cross-connect (OXC) at the Main Exchange (ME). The OXC maps the wavelength channels ($K.L$) to a number of transceivers N_R of the OLT. Use of an OXC, composed of fast Semiconductor Optical Amplifier (SOA) gate arrays, is preferred over an electrical switch, since this reduces the number of required transceivers at the OLT. Moreover, switching in the optical domain allows for multiple line rates in the system and the possibility to by-pass a particular transceiver in the case of maintenance or other service disruptions.

Network Path Protection between the OLT and the LSC 2 is achieved by using a protected multi-fiber ring architecture to connect the AWGs to the OLT, where a dedicated fiber is used for each AWG. At the OLT location, K protection switches are present, each either selecting the clockwise or counter clockwise direction in the ring. This configuration corresponds to a distributed LSC 1 power splitter.

The Last Mile Network provides a variety of access networks, each connected to at least one Leaf Router. Within HARMONICS, both a fixed (VDSL) access technology and a wireless (Hiperlan/2) access technology are studied for their seamless integration with the OFN. A detailed description of these last mile networks and their QoS possibilities however, falls outside the scope of this paper.

3 End-to-End Quality of Service

Performing basically the same role as IP —currently the layer 3 *best-effort* inter-networking protocol—, DiffServ has the added value of being able to offer end-to-end L3 QoS while offering scalability and compatibility with the existing IP.

Of course, if end-to-end QoS is to be guaranteed, *shared* layer 2 networks have to be QoS enabled and a QoS mapping between layer 2 and layer 3 has to be provided. Shared layer 2 networks involved in HARMONICS are the PON and the various last mile networks. Details on QoS implementation in the PON and QoS mapping between DiffServ and the PON can be found in Sections 3.2 and 3.3. QoS at layer 2 and the QoS mapping for the last mile networks are also investigated in HARMONICS but fall outside the scope of this article. The core networks (Internet backbones) are typically some layer 3 routers interconnected by constant bit rate (CBR) point-to-point links (which can be provided by a variety of layer 2 technologies with or without QoS). As such, there is no need to map L3 QoS parameters and connections to L2 QoS in the core networks[2].

3.1 QoS at Layer 3: Differentiated Services (DiffServ)

To cope with a variety of layer 2 technologies while providing end-to-end QoS, DiffServ ([2, 3]) is used at Layer 3. Within DiffServ, traffic marked with the same DiffServ Code Point (DSCP, [4]), called a *Behavior Aggregate (BA)*, receives the same per-hop-behavior (PHB) and thus the same QoS. Hence, DiffServ is very *scalable* regarding the number of flows, as only a limited

[2] *QoS-matching* between L2 and L3 is needed however: typically, a CBR point-to-point link is provided with an upper-bound on the delay (and eventually jitter). Those upper-bounds can be used to see which L3 QoS classes can be supported (*matched*) by these L2 links.

number (max. 64) of QoS classes are supported and the core routers only have to know about those DSCPs and their associated per-hop-behavior. All intelligence and computational intensive jobs (per flow or per BA classifying for DSCP (re-)marking, policing, shaping, ...) are moved to the edges of the networks where the number of flows can be handled. Those DiffServ edge and leaf routers[3] have to be configured dynamically as they contain elements (markers, shapers, policers, ...) which are BA- or flow-dependent.

Currently, the following DiffServ per-hop-behaviors are standardized: *Expedited Forwarding (EF)* guarantees the highest QoS and can be compared to a virtual leased line with such properties as assured bandwidth, low delay, low loss, low jitter. *Assured Forwarding (AF)* on the contrary is less stringent and only assures that the IP packets will be forwarded and not dropped if they are in-profile. There are no guarantees on delay and jitter. Of course, classical *best-effort* traffic (as in the current Internet) remains also possible and doesn't need any special treatment in the routers.

3.2 A novel MAC to support QoS at the WDM access feeder

The HARMONICS OFN is dominated by the characteristics of a conventional (single channel) PON system. In contrast however, the presence of the optical cross-connect (OXC) prevents the employment of familiar medium access control (MAC) schemes, at least at the OLT. When a number of single channel ATM PONs would be connected to the core network by means of an external single-channel ATM switch, they can operate their own MAC. By incorporating a multi-channel OXC, the HARMONICS system is able to exchange the capacity between different channels, but it has to perform the MAC for all wavelength channels together, as well as for the OXC itself.

Downstream. In the downstream direction, power splitting PONs implement the TDM allocation scheme in a relatively simple way by using a broadcast-and-select mechanism. The OLT attaches the destination ONU address to each data packet when it is transmitted, and the ONUs monitor the downstream data for their packets. The multi-channel WDM PON can perform the same, but here the MAC also needs to actuate the OXC to connect the channel of the destination ONU to a particular transmitter.

Upstream. The most delicate aspect of access control in TDM PON systems occurs in the upstream direction in the power combiner. To avoid collisions of packets from different ONUs, very accurate synchronization is required between their transmitters. This alignment is complicated by the different distances at which the individual ONUs are located in the field. To solve this, the ONUs observe a transmission delay that is established during a measurement procedure ("ranging").

Optical packet switching. An important issue is the choice of packet size.

[3] *Edge routers* are the routers at the boundaries of DiffServ domains working on a BA scale, while the *Leaf routers* are the first routers on the path from a host to the destination. The latter work on a per-flow base.

The use of variable packets (for higher layer protocols with variable packets) at the optical layer restrains the switching flexibility at the OXC considerably, since switching is only allowed at moments when gaps occur. By using fixed packet sizes, the MAC allows for flexible bandwidth allocation. A disadvantage is the need for segmentation and reassembly of network layer packets. The optical packets should be small to enable flexible allocation: the size of the smallest IP packet. The HARMONICS demonstrator will use 160 and 100 byte packets for downstream and upstream respectively, corresponding to 1.28 μsec. This keeps the relative overhead below 20%, low enough to allow for a usable bandwidth of about 1Gb/s downstream and 0.5Gb/s upstream. Unfortunately, different segments of a single packet still need to be transmitted to the same OLT receiver. Otherwise extra switching functionality is required to re-route the segments to the same reassembly unit.

Access control and allocations. For packets traveling downstream, there are no problems to access the medium (the fibers) as they all depart from a central point (the OLT). Upstream however, ONUs don't know when other ONUs are sending, so access control is needed and the upstream direction is the main challenge of the MAC protocol. Access control can be seen as a continuous process involving three stages:

Assessment. The central controller (residing at the OLT) must be informed when an ONU demands access. Within HARMONICS, there are 2 types of allocations possible in the optical feeder network. A *static* allocation is installed via the management framework and reserves a constant bit rate. A *dynamic* allocation however is allocated on the fly when there is data available at the ONUs and is done by the ONUs sending requests to the central controller (piggybacked to upstream packets or with special packets, called minislots). These dynamic allocations are typically used for Best-Effort traffic while the static ones are usually used for QoS connections.

Scheduling. The controller determines which ONU is granted access. Detailed information about this falls outside the scope of this paper.

Notification. The ONUs that are granted access are informed. The broadcast nature of the downstream traffic in PONs makes it attractive to apply in-band signalling. Even when no packet is addressed to it, an ONU can read every transmitted packet (which by the way illustrates the need for encryption in PONs). By attaching a second address to the downstream packets, the OLT is capable of submitting *permits* for every upstream packet. When an ONU receives a permit, it is granted to transmit a packet upstream, observing the time delay that was established during the ranging procedure. For the static allocations, the central controller at the OLT sends permits downstream as needed to cope with the made reservation. For dynamic allocations however, the packets are queued at the ONUs waiting for permits coming downstream answering the upstream dynamic requests (see *Assessment*).

3.3 Mapping of DiffServ QoS (L3) to the optical feeder QoS (L2)

The HARMONICS architecture is DiffServ-based at layer 3 to allow applications and users to select the network service (of which EF, AF and BE are standardized) that best suits their needs.

On the other hand, the MAC at layer 2 in the OFN considers only two kinds of traffic: firstly traffic with certain QoS constraints which has to be reserved by means of the connection management framework (e.g. EF or AF which need reserved resources to avoid losses, high delays and jitter) and secondly traffic for which dynamic permits are requested by the ONUs and for which no QoS can be guaranteed (e.g. BE).

Note that for the downstream case, EF, AF and BE traffic receive the same QoS once they're *in the PON*, but a differentiation is made at the HARMONICS edge router which has basic DiffServ functionality and as such prioritizes EF over AF over BE. For the upstream case however, EF and AF traffic is queued in the static allocated queues in the ONUs for which permits are generated automatically, while BE traffic is stored in the dynamic queues for which permit requests have to be sent by the ONUs. Hence, upstream, differentiation between EF, AF and BE is made both at the HARMONICS leaf router and in the PON.

4 End-to-End QoS Connection Management

To set up end-to-end connections with QoS guarantees, all networks along the path should be informed and queried (admission control) if a new connection can be provided. E.g. for DiffServ domains, this encompasses the configuration of leaf and edge routers (classifiers, DSCP markers, shapers, policers, ...) upon a positive response of the admission control for that domain. For the OFN, admission control and the subsequent configuration of the MAC protocol has to be fulfilled. Therefore, a management framework is proposed which takes care of these tasks. Note that this connection setup phase is only needed for connections with a higher QoS than best effort traffic, which will be the minority of the traffic. Hence, there will not raise problems of scalability regarding the number of connections.

The communication between the management components is based on CORBA (Common Object Request Broker Architecture), because of the object-oriented framework, its *standard* mappings to multiple O–O languages and because it may become the ubiquitous technology for future heterogeneous distributed systems [7]. To provide a smooth communication between the CORBA components, on boot up of the management framework, high QoS paths with a dynamically adjusted bandwidth are reserved.

4.1 Concept of Layer Networks and Layer Network Coordinators

To ease the end-to-end coordination and management of different administrative domains and technologies, a generic layering and hierarchy model was

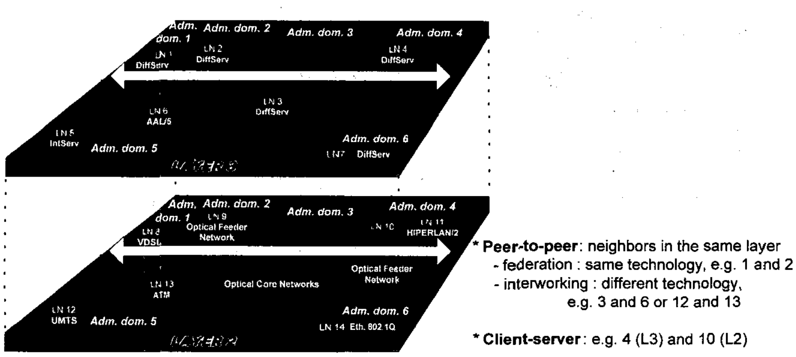

Figure 2: Layers, Administrative Domains and Layer Networks (LN)

introduced following the *Divide et impera* concept. The architecture and used terminology is based on proposals by the TINA Consortium ([8]), although adapted to be more consistent and applicable.

The most important concept is *Layer Network* (Figure 2). A Layer Network is a network consisting of a single technology (e.g. DiffServ, ATM, ...) and is restricted to a single administrative domain (e.g. an operator). One domain can contain several Layer Networks, each with another technology, as shown in the figure. Within the TINA Consortium, the term Layer Network is used to describe all network equipment of one technology in the *whole* world, but this isn't a useful definition because of scalability issues.

Separate Layer Networks can have different relationships with each other as shown in Figure 2. Both network layers 2 and 3 in the figure have the same Administrative Domains, which is only to not overload the figure. It would be perfectly possible e.g. that Administrative Domains 1 and 2 at L3 are only one Administrative Domain owned by one provider and as such there would be only one DiffServ Layer Network.

A logical next step in the concept of Layer Networks is to introduce the *Layer Network Coordinator (LNC)* as a software entity which is responsible for the coordination of a single Layer Network and the negotiation with neighboring Layer Networks. Here we see why this terminology as used in the TINA specifications — one LNC for the whole world — isn't very logical, in view of the structure of the Internet with the different domains. The LNCs are technology dependent and are only *logically* a single component. *Practically* they can be distributed by advanced distributed software techniques and load-balancing algorithms which make a scalable approach perfectly possible.

Applied to the HARMONICS project, Figure 5 shows the different Layer Networks with their respective LNCs. This is the reference architecture which will be described in detail in the following sections. On top of the LNCs, optionally a service management architecture as described in [9] can be used to negotiate QoS matching at the application level (e.g. VoIP codec parameters).

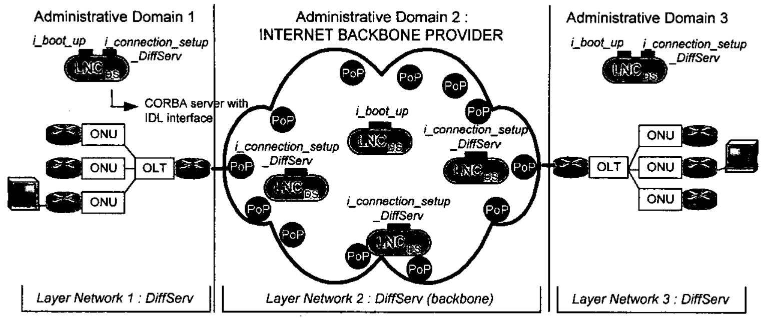

Figure 3: End-to-end layer 3 connection management: a Layer Network Coordinator (LNC) for each Layer Network (PoP = Point of Presence)

4.2 DiffServ layer 3 multiple domain management

Within the HARMONICS project, DiffServ is the single technology used at layer 3 and as such only *federation* between different DiffServ Layer Networks is considered at that layer. At layer 2 a variety of technologies are under study, but the *interworking* between different layer networks can be handled by the common layer 3 technology, because a QoS mapping between DiffServ and the various layer 2 technologies is already being developed for the intra-Layer Network *client-server* relationship.

Figure 3 shows a typical end-to-end situation and the federation relationships from a DiffServ layer 3 viewpoint (for simplicity Last Mile Networks are not drawn explicitly). Of course, instead of a backbone of only one provider, multiple backbones (and hence multiple Layer Networks) could be drawn. Note however that an average flow through the current Internet crosses about 1 or 2 backbones and 2 access networks, which can be checked on various `traceroute` websites. A LNC_{DS} (Layer Network Coordinator for DiffServ) is responsible for its DiffServ Layer Network and also for the negotiation with peering Layer Networks. The LNCs for the access feeder networks (domain 1 and 3) are logically and physically centralized in their respective domains as this imposes no scalability problems. A quick calculation with the Erlang formula [5], gives a worst-case scenario: the 64 channel OFN has a total amount of 64 Gbit/s downstream and 32 Gbit/s upstream. If this total bandwidth *would* be used for video-conferencing calls with a 2.5 Mbit/s bandwidth and we suppose a 0.0001 blocking probability, then there would be a load of approx. 30000 erlang, good for 6000 flows/minute with a mean duration of 5 minutes. This would impose a load on the management architecture of only 100 flow setup requests per second which is an upper-bound as (i) VPNs or video-conferencing calls will take more than 2.5 Mbit/s, (ii) only part of the bandwidth will be used for QoS connections and (iii) the duration of these calls will be longer than 5 minutes. It should be possible for the multi-threaded management components, which parallelize the different requests, to handle these. The LNC for the core network however is physically distributed and as such each sub-component only handles part of the flows. As described in Section 3, all configurable DiffServ leaf and edge routers are situated at the edges of the domains and as such it seems logical to bundle a couple of edge routers and manage them by a physically separated component, embodied by a CORBA object.

Regarding the IDL interfaces, each LNC_{DS} has two types of interfaces: the `i_boot_up` interface which is meant for initializing the management architecture and the `i_connection_setup_DiffServ` interface which is used for setting up connections, see also Figure 4. The object references to the `i_boot_up` interfaces of peering Layer Networks are well-known (i.e. they can be looked up in a CORBA Naming Service or they are manually provided by the ISP) and are used by an LNC to get the object references to the objects with a `i_connection_setup_DiffServ` interface.

An initialization scenario goes as follows: when the LNC_{DS} of Layer Network 3 boots, it requests the LNC_{DS} of domain 2 for a reference (or list of references, `conn_setup_list`) to an object(s) implementing the `i_connection_setup` interface while providing the network address (`address`) and technology (`peer_technology`) of domain 3. The latter two make it possible for the LNC of domain 2 to return the object reference to the most appropriate object (which is responsible for the right edge router and which speaks the same QoS parameters). Next, the LNC_{DS} of domain 3 registers (`register`) itself (together with the network address and the type of technology of domain 3) with that particular object of the LNC_{DS} of domain 2. From now on, both LNCs can reach each other to set up connections via the `setup_connection` interface method. As the LNCs have a *federation* relationship with each other, the QoS parameters are DiffServ related and the `DSCP` is the only QoS parameter in DiffServ (for simplicity, we assume that the DSCPs in the 2 domains are the same. This isn't a big problem as the DSCPs for EF, AF and BE are standardized and non-standardized PHBs will be very likely supported by only one of the domains). The `min_bandwidth` and `wanted_bandwidth` parameters are the minimum needed and the wanted bandwidth to be reserved, while `wanted_bandwidth` will contain the effectively reserved bandwidth on return. The `BandwidthDescriptions` can be described in different manners (as described in the DiffServ MIB [6]): TokenBucket, AverageRate, Single Rate 3 Color (RFC2697), Two Rate 3 Color (RFC 2698), Time Sliding Window 3 Color Marker (RFC 2859). The `source_address` and `destination_address` can be both an IPv4 or IPv6 address:

```
struct IPv4_address {
 unsigned long address; // 4 byte addr.
 octet mask;            // netmask(bits)
 unsigned short L4_port;// layer 4 port
 octet protocol;        // layer 4 prot.
};
```

```
typedef octet IPv6_addr[16];
struct IPv6_address {
 IPv6_addr address;      // 128 bit
 octet mask;             // netmask size
 unsigned short L4_port; // L4 port
 octet protocol;         // L4 prot. };
```

A typical connection setup scenario might look like this: a user in domain 3 wants to start a video-conferencing session with a user in do-

```
enum relation {federation, interworking, clientserver};
struct conn_setup_iface_ref { i_connection_setup      iface_ref;
                              relation                type;
                              string                  peer_technology;  };
typedef sequence<conn_setup_iface_ref> conn_setup_list;
interface i_boot_up {conn_setup_list get_conn_setup_iface(in any address,
                                                          in string peer_technology); };
interface i_connection_setup { void register(in i_connection_setup peer_lnc_ref,
                                             in any peer_address,
                                             in string peer_technology);
                               boolean tear_down_connection(in unsigned long flow_id);
                               typedef sequence<unsigned long> flow_id_list;
                               void release_connections(in flow_id_list flows);  };
struct BandwidthDescription { string Type;
                              unsigned long Rate;
                              unsigned long BurstSize;
                              unsigned long Interval;  };
interface i_connection_setup_DiffServ : i_connection_setup {
   unsigned long setup_connection(in any source_address,
                                  in any destination_address,
                                  in BandwidthDescription min_bandwidth,
                                  inout BandwidthDescription wanted_bandwidth,
                                  in octet DSCP);  };
```

Figure 4: LNC_{DS} IDL interfaces `i_boot_up` and `i_connection_setup_DiffServ`

main 1 and requests his LNC_{DS} (by means of e.g. RSVP, CORBA, ...) for an end-to-end connection. The LNC_{DS} knows from its routing information which peering LNC_{DS} CORBA object it has to contact. The latter looks up its routing information (typically this routing information will be gathered from the Border Gateway Protocol, BGP) to know which outgoing `i_connection_setup_DiffServ` object in the core domain it has to contact, which will in turn contact the LNC_{DS} of domain 1. Each LNC performs Flow Admission Control (FAC) (IP is inherently connectionless, so Connection Admission Control (CAC) is a bad term. However, there is always a concept of *flow*, which means a stream of closely related packets, e.g. for a video-conferencing session.) and configures the necessary edge and/or leaf routers for its Layer Network. In case of an underlying network (client-server relationship) which has to be configured to cope with the new connection, e.g. in case of the access feeder networks, the underlying LNC_{OFN} has to be contacted which will take care of the configuration in its Layer Network (Figure 5).

4.3 Optical feeder resource management

Future PONs, of which the main advantages are the simple maintenance and low cost [10], should be able to cope with many different classes of traffic. Therefore, the HARMONICS optical access feeder Layer Network is controlled by three entities (Figure 5):

- LNC_{OFN} which takes control of the configuration of the HARMONICS edge and leaf routers and which converts the IP addresses to ONU numbers before forwarding new requests to the RM.
- Resource Manager (RM) which has a link-oriented control of the OFN.
- MAC which has a packet-oriented control of the OFN.

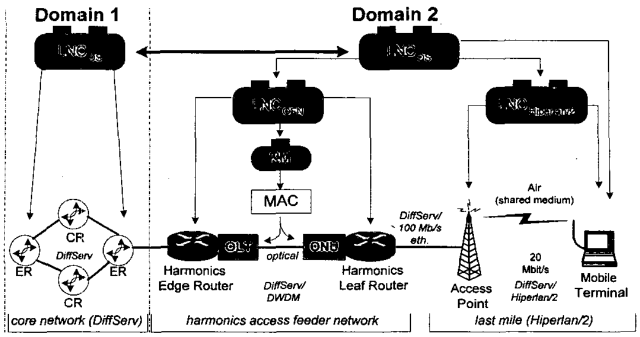

Figure 5: End-to-end management for the different layers and technologies

The RM performs the flow admission control for the OFN by accepting/ rejecting new *prioritized* flows (best effort is handled by dynamic permit requests by the ONUs) according to the QoS, the available resources and the requests received from the LNC_{OFN}. The RM communicates the allocation of resources needed for the prioritized flows to the MAC, which performs the actual assignment of wavelength channels and time slots. The link-sharing mechanism could be applied to control the sharing of the PON by different classes of traffic. This traffic can be mapped into a hierarchical structure [11]. At the top level there is the link that has to be shared by different traffic, which in our case is one wavelength at one WDM link. Several ONUs share this wavelength through the power splitter of LSC 3 (Figure 1). Each of these ONUs has multiple customers connected, each customer having several applications with different QoS requirements.

The problem is how to allocate bandwidth among all the kinds of traffic. The proposed solution consists of two allocation types: a *pre-reserved* allocation and an *adaptive* allocation. The former reserves a certain bandwidth for each kind of traffic of each customer connected to the PON.

The flows' pre-reserved values can be modified based on statistics of the traffic generated by each customer (which can be done at the RM based on regular feedback sent by the MAC about the real BW used). Because the real demand distribution for the link won't be always the same as the pre-allocated one, adaptive allocation of bandwidth is activated, which means re-assigning any remaining bandwidth to traffic types that request more bandwidth than already reserved to them for the setup of new connections.

In order to perform bandwidth allocation, the RM receives a connection request from the LNC_{OFN} similar to the one (`setup_connection`) shown in Figure 4 but with ONU identifications instead of IP addresses. The BW_{peak}, BW_{min} and the DSCP will determine whether this connection can be merged in the pre-allocated BW of this kind of traffic and if necessary, how much bandwidth has to be adaptively allocated. Of course, this adaptive allocation will be closely related with the reshaping at the leaf and edge routers and with the MAC wavelength and time slot assignment.

5 Implementation and Field Trial

To validate all the different parts, two lab trials (one embracing the optical components: OLT, ONUs, AWGs, ... and one comprising the higher layer management components, the L3 routers and the last mile networks) will be organized starting from May 2002 within the HARMONICS project. These lab trials will result in a field trial in Berlin and Darmstadt, Germany with real users, a VDSL and Hiperlan/2 last mile network and a.o. some video-conferencing and Video-on-Demand services (Figure 6) starting November 2002. For the second lab trial and the field trial the Optical Feeder Network and the MAC protocol will be emulated on one or more PCs running Linux and the Click Modular Router software [12] which is also used for the IP routers.

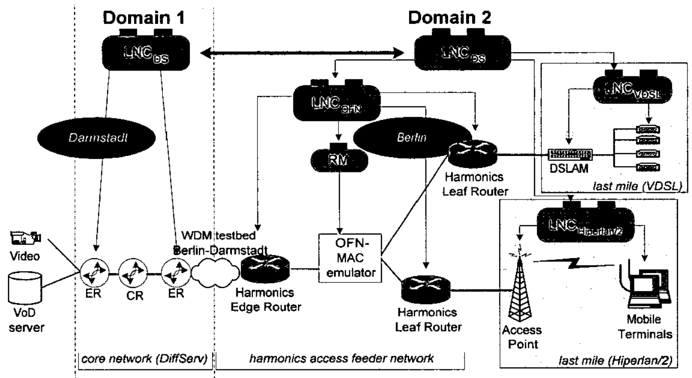

Figure 6: Lab and field trial setup

6 Conclusion

This paper described a novel generic CORBA-based end-to-end QoS resource management framework applied to a DWDM Optical Feeder Network (OFN) (Section 2) as studied in the HARMONICS project. To provide end-to-end QoS, IPv4/IPv6 DiffServ is used at L3, managed by the new connection management framework (Section 4). At layer 2, a novel MAC protocol (Section 3.2) is proposed for the HARMONICS OFN, supporting both time slot and wavelength allocation while guaranteeing QoS. The QoS mapping between DiffServ and the OFN is described in Section 3.3. For the last mile networks, advanced technologies as VDSL or Hiperlan/2 which support QoS, are used but their L2 QoS and the QoS mapping are not addressed here.

Further work includes completion of all components and integrating them in a test bed to investigate the performance and scalability. Finally, a field trial experiment will demonstrate the feasibility of end-to-end connectivity with guaranteed Quality of Service using packet switching in the OFN.

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