It’s ALIVE! Getting to Successful R-PHY Deployment: Do’s And Don’ts

A Technical Paper prepared for SCTE•ISBE by

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Introduction

This paper is an operational overview of one of the first Remote PHY deployments in the world, at a Danish operator – Stofa. Being an early adopter, the entire process of selecting the technology, planning the new network design, and deploying the products was an uncharted territory. Stofa and ARRIS, the selected vendor for the project, have learned many lessons from the experience, which are all detailed in this paper.

In addition, we have analyzed the benefits that the Remote PHY network upgrade has provided to the operators, including measured improvements in signal to noise ratio in the field and space and power saving in the headend.

The results we present demonstrate the great benefits transitioning to Remote PHY can achieve. First, there is a clear improvement in SNR values in the upstream (US) direction, which will allow Stofa to go to higher modulation orders using DOCSIS 3.1 US. In the downstream (DS) direction, results are less conclusive. The transition to R-PHY was accompanied with a move of DOCSIS D3.0 channels to higher part of the spectrum, which may have countered the improvement. In addition, some elements in the network like the drop cable were not replaced, and may affect the measured signal-to-noise ratio (SNR) at the cable modem (CM) side.

Second, we analyzed the space and power saving in the headend that resulted from the migration from the previous network architecture (Modular-CMTS) to Remote PHY. The analysis showed significant space savings – going from about 70 RU to 18 RU in the headend for the MAC core and network support, and less than half the power required in the headend for supporting these functions. In addition, the operational complexity is dramatically reduced, due to the major reduction in devices that need to be managed, and the automated management that is introduced. As part of the project, Stofa's ability to do proactive network management actions is greatly improved, as well as their ability to effectively grow their network and customer offering without any truck rolls or field work.

All these benefits will be reviewed in the paper, as well as the steps Stofa took in order to prepare for the deployment, and successfully deploy the new technology in the field, serving thousands of subscribers.

The Story Unfolds…

1. Market

1. Cable Market Driver – the "Need for Speed"

It cannot be denied that the "need for speed" is dominating our cable operators market at a growing rate. Operators are very mindful of the highly competitive landscape they operate within, and about the need to increase some of the subscribers' bandwidth by 50% annually. We can see the projected bandwidth demand growth according to Nielsen's law in Figure 1 below:

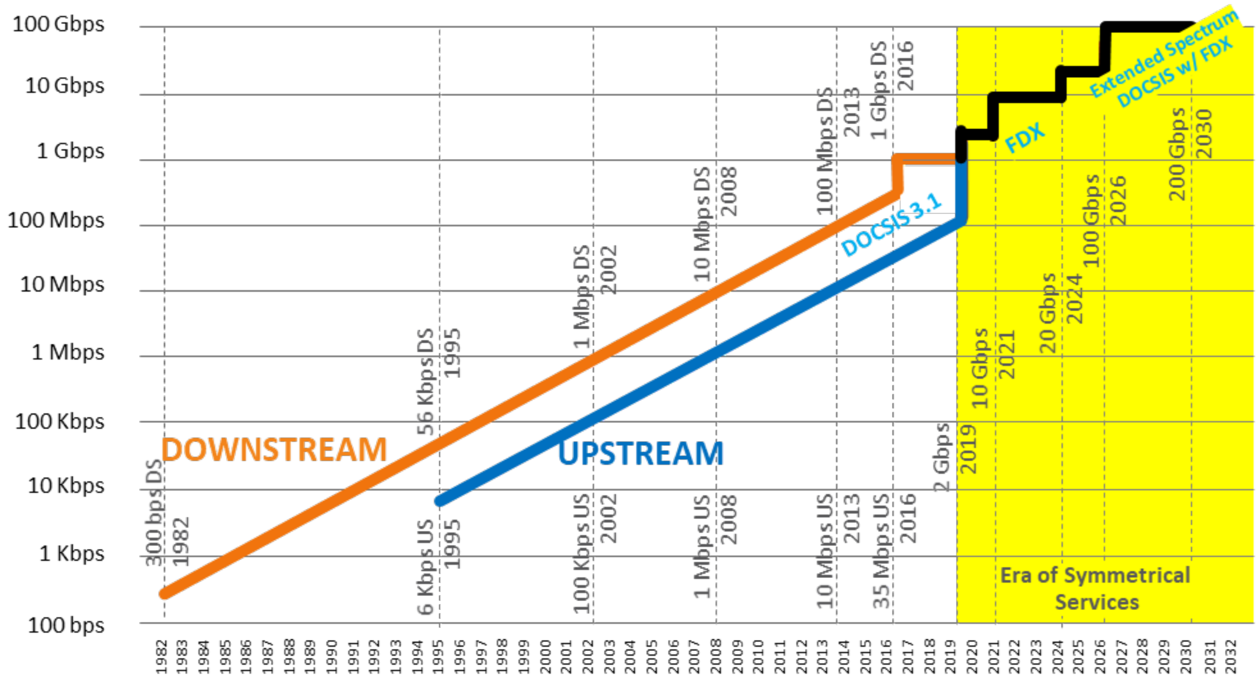


Figure 1 - Nielsen's Law of Internet Bandwidth (Growth Rate = 50%/YEAR for high end subs)

In order to deal with that rapid growth in the demand for bandwidth, operators are searching for new technologies and architectures that can help them supply those speeds and new services, using an efficient scalable design, with predictable and controllable cost of ownership.

Operators may consider making changes to their headend network, their nodes and amplifies, their Service Groups sizes, the modulation profile used on different areas of the plant and more. The challenge for an operator is to choose the right mix of adjustments that can help them optimize their network and supply their subscribers' demand.

In this paper we will review the case of Stofa, a Danish operator that has chosen to introduce DOCSIS 3.1 and Remote PHY architecture into their network, to handle those mentioned challenges.

Many operators are seeing similar challenges, and therefore we are seeing a significant change in the cable access market, while operators are considering their next technological upgrade and their future network evolution.

In Figure 2 we can see the S&P Global (Kagan) forecast for market transition:

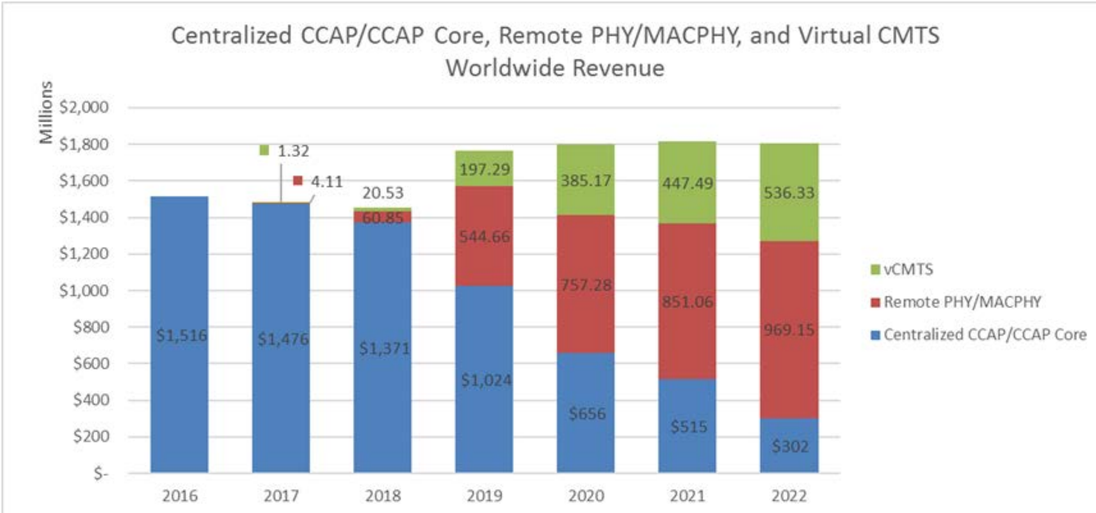


Figure 2 - CCAP/Remote Architectures Market Revenue Forecast

This chart shows clearly the expected transition to Distributed Access Architectures (DAA), which include Remote PHY and Remote MACPHY. Starting gradually from this year with early trials and limited deployments, we can see a projected growth in the penetration of the new technologies starting significantly from 2019 and onwards.

We can attribute this timing to multiple factors:

- **Product Readiness -** Equipment providers have started to offer Remote PHY products already early this year, and they will get some experience with initial early deployments [Silbey]. However, some operators are choosing to wait for the technology to mature, or for a specific flavor of the products to become available before they begin deployments.
- **Network Planning -** Architectural upgrades such as the transition to DAA require many planning phases and a lot of thought. As will be discussed later in the paper, operators have to go through the considerations of which access architecture is the best fit for them, and they must also go through detailed planning activities in order to be prepared for the transition from a network readiness perspective, as well as from an operational perspective.
- **Existing Unrealized Capacity** – Many operators are currently using dense integrated CCAPs, deployed in the last few years. Many of these systems still have unused capacity that can allow for services expansion with licenses addition only. So, for those operators the need to upgrade their network may be less pressing. If they do upgrade, then they may opt to utilize architectures that permit them to re-use their recently-deployed equipment.

1.1. Distributed Access Architectures (DAA)

Distributed Access Architectures represent an evolution in the cable access network structure and operations. The drivers for DAA (and specifically Remote PHY) are detailed in section 1.c. They include the desire to bring fiber closer to the home (in order to be better prepared for FTTx architecture), the need to reduce space and power in the headend, and the drive to provide higher bandwidth to the subscriber.

In order to do that, the cable industry designed a variety of Distributed Access Architectures, where parts of the traditional integrated CMTS or CCAP are moved to the node structure, closer to the subscriber. The different architectures vary in the amount of functionality that is being moved to the node, and the changes the operator will be making in their headend design, and specifically the video portion of that.

If we start by looking at the **Centralized Access Architecture in** Figure 3, we can see that all CMTS and CCAP functionality is centralized in the headend or hub, supporting high speed data, voice and video services. The processed radio frequency (RF) signals are transmitted to the optical node via analog carriers over fiber, where they are converted to analog signals over coax.

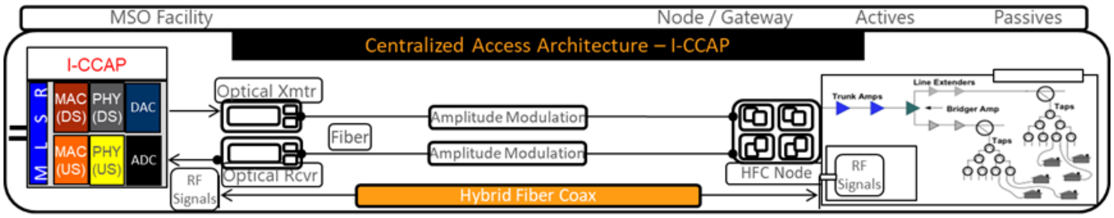


Figure 3 - Centralized Access Architecture Diagram

With **Remote PHY in** Figure 4, the PHY part of the processing is moved to the node, meaning the QAM modulation, FEC and DAC/ADC. The headend equipment is responsible for the MAC processing, and is transmitting the MAC-processed signals to the node via digital optics the Converged Interconnect Network (CIN).

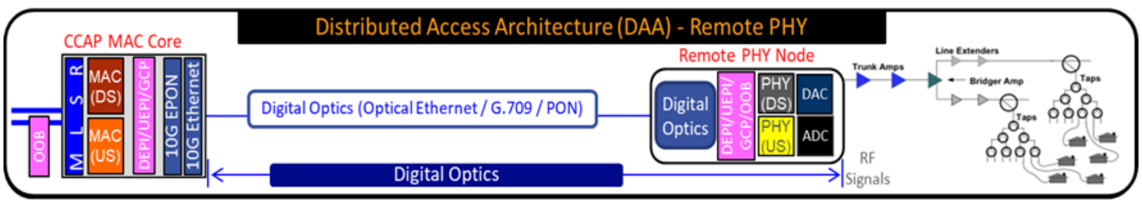


Figure 4 - Distributed Access Architecture – Remote PHY Diagram

The internal components of a Remote PHY system include (per [R-PHY-spec]):

- Ethernet Interface
- Clock Circuitry
- Remote PHY Pseudo-Wire Interface
- Common Layer 1 PHY Circuitry

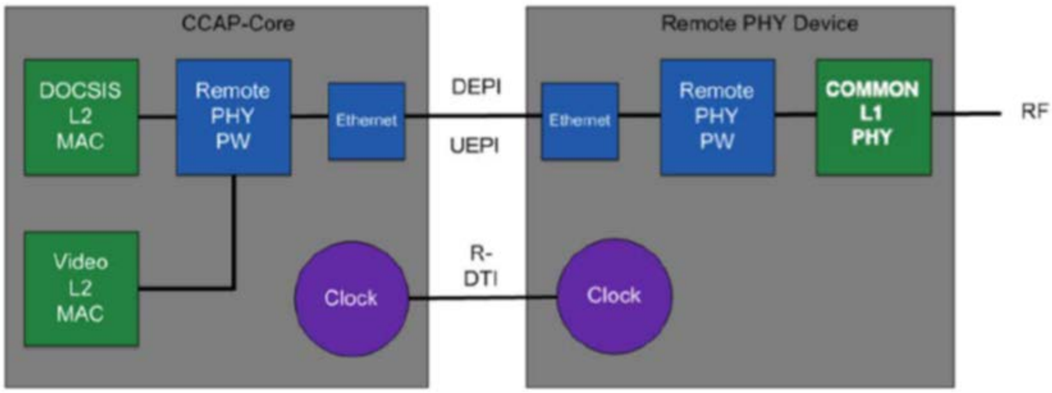


Figure 5 - R-PHY Internal Components

As can be seen in Figure 5, there is a clock component at every device, and those clocks need to be synced, to allow for proper operation of the Remote PHY solution. The synchronization requirements are detailed in the DTI spec that is part of the Remote PHY set of specifications [R-DTI Spec].

Another type of DAA, still being defined under a specification process, is "Flexible MAC Architecture" (aka Remote MAC and PHY, also sometimes referred to as Remote CCAP). In this flavor of DAA, the traditional functions of a CMTS (both MAC and PHY) are moved to the node. The data is transmitted to the node from the north bound router over IP network.

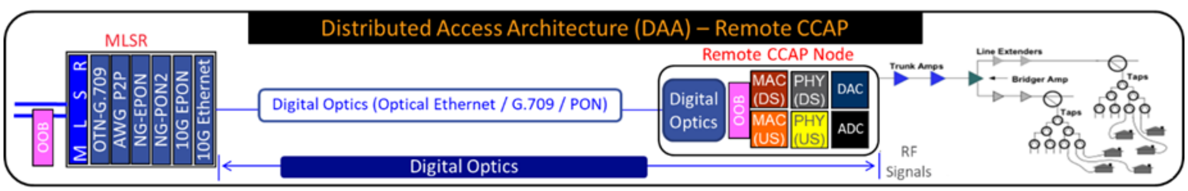


Figure 6 - Remote MAC PHY Architecture Diagram

We will not discuss the transition to Remote MAC PHY, depicted in Figure 6, within this paper.

1.2. DOCSIS 3.1 Introduction

DOCSIS 3.1 is the relatively new broadband data specification, designed to increase the DOCSIS services capacity on the existing HFC networks. DOCSIS 3.1 relies on:

- OFDM
- LDPC
- Energy Management
- Hierarchical QoS
- Active Queue Management
- Advanced Timing Support.

The capacity D3.1 is expected to offer is summarized in the Table 1.

Table 1 - DOCSIS Evolution increases HFC network capacity (Source: CableLabs)

	DOCSIS 3.0	DOCSIS 3.1
Upstream	0.1 Gbps	1-2 Gbps
Downstream	1 Gbps	10 Gbps

Since the DOCSIS 3.1 spec completion, in 2013, we are seeing gradual deployment of D3.1 services. Some reasons for the slow adoption are: Headend equipment readiness, CPE device availability, and compatibility issues between the two given it is a new spec. Some operators are also delaying the DOCSIS 3.1 introduction due to the large investment required for CPE device upgrades.

Figure 7 shows the forecast for D3.1 services deployment.

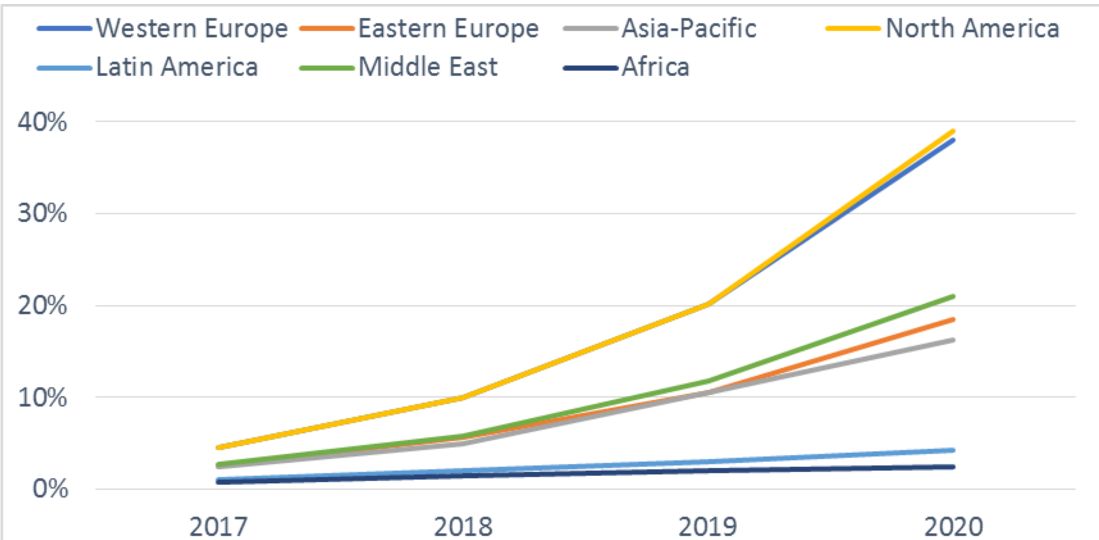


Figure 7 - DOCSIS 3.1 Deployment Forecast (Source: ABI Research)

2. Company (Stofa) overview

2.1. Company overview

Stofa is located in Denmark and is delivering broadband services to about 500K cable households. Stofa is Denmark's second largest provider of television, broadband, and telephony.

Stofa's customers are mostly antenna associations – organizations responsible for providing infrastructure services to a community of usually a few thousand subscribers. The services they are responsible to provide include high speed data, voice, and video (legacy QAM video) in high quality to their subscribers.

2.2. Network architecture at the starting point

About 60% of Stofa's footprint is rural, but there is a strong concentration of MDUs in Denmark's major cities. As is typical in most of Europe, cable runs are buried rather than aerial (as is largely the case in the US outside urban areas).

Prior to the network upgrade project discussed in this paper, Stofa had been deploying a Modular CMTS (M-CMTS) architecture. Stofa had deployed the CMTS in their headend, and the associated EQAMs were usually deployed in the antenna facilities location.

Stofa has been deploying services using an N+5 plant configuration, meaning 5 levels of amplifiers after the fiber node. Before the upgrade project, for their high-speed data service groups, they had been deployed with a 1 downstream: 2 upstream node combining ratio.

Stofa has fiber links deployed between their headends and regional hubs. Their topology is such that the typical maximum distance between the headend and the node location is 10 km.

2.3. Motivation for network upgrade

In 2016, Stofa decided to launch a project for planning of a network upgrade, and started searching for the best fit in terms of network architecture and products. The Stofa drivers for the network upgrade included:

A. **Market competition** – growing competition in the Danish market was driving Stofa to look for advanced solutions to increase the bandwidth offering to the subscriber. Stofa chose to upgrade their network to DOCSIS 3.1, and go from a 860 MHz plant to a 1.2 GHz plant for DS, and up to 204MHz in the US. These upgrades were targeted to increase the capacity Stofa planned to offer their customers on both the US and the DS directions: first, by transitioning to D3.1 and reaching a higher modulation order; and second, by increasing the amount of spectrum available for the different services.
B. **Transition to digital fiber** – The year-on-year growth in both physical fiber count and optical wavelength division multiplexing (WDM) filters to support the growing number of optical nodes was becoming a real issue for Stofa in regards to physical space at the major headends. Either much better utilization of existing fibers or new larger headends was needed. Digital fiber solves this issue by providing the benefits of not only multiplexing many nodes onto the same fiber (not completely unlike WDM) but also by providing the benefits of statistical multiplexing (Customer A not using bandwidth at the "exact" same time as Customer B). The use of the IP protocol on top of Digital fiber also enables dynamic sharing of traffic across different fibers - something that was unthinkable in the past.
C. **Consolidating hub sites** – Stofa was challenged by the space and power in the hub and headend locations. The operational cost of those facilities were a burden on the Stofa budget, and they were looking to reduce the space required for network infrastructures, and longer term they planned to consolidate many of their headend's into a centralized data center.

3. Operators Drivers for R-PHY, and Stofa's Specific Drivers

3.1. Drivers and benefits of Remote PHY

Potential drivers for DAA architecture include (also according to [Cloonan]):

A. **Transition to digital optics** – with DAA, the transmission from the headend to the nodes is done using digital signals on the fiber network, as opposed to the centralized architecture, where it is done over analog signals on the fiber network. The digital transmission allows for more lambdas to be populated over one fiber. With digital fiber, an operator can use up to 80 lambdas on one fiber, whereas with analog optics the maximum is about 32. This allows the operator to better utilize their existing fiber network and drive more bandwidth using it. Digital fibers also allow for greater distance between the headend or hub and the node, allowing the operator to centralize their MAC core functionality in data centers feeding remote nodes. In addition, operation of digital fibers is perceived easier than analog fibers, that may require frequent tuning and adjustments. The transition to IP brought in many operational benefits, and significantly increased the fibers' capacity.

B. **Headend space and power reduction** – DAA's main principle is about moving functionality out of the headend and hub, and down to the plant. The reduction of functionality in the HE drives lower space and power required for the processing functions, allowing for operational saving on the facility maintenance, and potentially hub consolidation. See previous study conducted on space and power requirements for the different access architectures [HFC-Green-ULM].
C. **Better SNR at the "end of the line"** – DAA moves RF signal processing from the headend where it is transmitted to the node with AM fiber, and puts the RF processing in the node eliminating the potential signal degradations from AM fiber, and can improve SNR resulting in the use of high orders of modulation with more data transported over the same bandwidth
D. **Facility consolidation** – As discussed, Remote PHY can help with facilities consolidation, due to space and power saving. In addition, R-PHY allows for the headend/hub to be more remote from the node and subscriber, since the fibers used to carry the data are carrying digital signals, which have less distance limitations. So with R-PHY, the facilities can potentially be consolidated to reduce facilities and maintenance costs for the network.

Additional benefits may apply specifically to Remote PHY:

E. **Ability to reassign MAC Processing** – when using R-PHY, the MAC processing capabilities are centralized in the MAC core. The Remote PHY Devices (RPDs) can dynamically be moved from one core to another per need, potentially for load balancing purposes. This allows the operator better resource efficiency and flexibility.
F. **Ability to select best-in-breed from CCAP Cores and Nodes –** Remote PHY spec by Cable Labs [R-PHY Spec] is designed such that cores and nodes from different vendors can interoperate, when they are both complying to the spec.
G. **Little change in the provisioning, configuration and management systems** – Remote PHY architecture defines that provisioning and configuration of the nodes be done from the MAC Core. Having one centralized point of configuration is similar to the way DOCSIS networks operate today, so minimal changes have to be done in back office systems and operational models.
H. **Better path towards virtualization** – centralizing the MAC Processing in one location creates a better path towards virtualization, since the MAC processing function is easier to virtualize. In the future, physical appliances such as the MAC Core can be virtualized and moved to off-the-shelf servers, which will further reduce the cost, space and power, and enhance the flexibility of resources assignment.

3.2. Stofa's Drivers for R-PHY

Of the potential benefits of Remote PHY, a few were more impactful in Stofa's decision to migrate their network to remote PHY.

The headend space and power saving, along with potential facilities consolidation were very important to Stofa. The cost associated with maintaining their headends and hubs is a considerable part of their OPEX, and Stofa were looking to both downsize in the headends, and also remove processing equipment from the local antenna associations / communities.

Better signal quality or SNR at the subscriber location was another driver for the project. Stofa's market is very competitive, and Stofa had to improve their existing capabilities to support the market's demand. Better SNR will allow Stofa to migrate to D3.1 and materialize the benefits it will provide with higher modulation orders, which will create more capacity to the subscriber without changing the "last mile" wiring.

A strong motivator for Stofa to make the large resources investment in the project is the future expansion of the network as forecasted from their traffic engineering numbers. In the coming years, Stofa will have to continue to expand their services, growing the capacity provided per subscriber, in order to remain competitive. The current investment in the new technology (with a lot of room to grow) will allow Stofa to add only licenses in the next network upgrade cycles. They will not need to send technicians to install anything, but rather will only have to remotely change the configuration on the nodes already in the field.

In addition, Stofa likes the R-PHY architecture that allows them to keep the expensive and more complicated equipment (hence MAC Core) in the headends, which are owned by Stofa. This allows them better control over the installation environment, and a future path toward virtualizing these functions and centralizing them in data centers.

The centralization of the MAC core processing also has other benefits for Stofa.

First, the single provisioning interface (for a MAC core) allows Stofa to do minimal changes in their provisioning system, and back office tools. Some automation will be required to support the R-PHY nodes, but other changes are minimal which reduces the cost and complexity of this upgrade project. In addition, it also simplifies the training the Stofa personnel will have to take, in order to manage all configuration items on "one box". That applies for both the engineering teams and the operational teams debugging issues on the system.

Lastly, the Remote PHY solution Stofa has chosen allows them to converge all customer services on one platform: DOCSIS, VOD, and broadcast services. All these are processed by the MAC Core and being transmitted over digital fiber to the R-PHY node. The convergence allows for operational simplicity (since data path is unified for all services), and Stofa is also benefiting from sending the video signals efficiently over digital fiber. Other architectures for video transmission exist in the market, but Stofa decided to go with the converged one because of the operational simplicity it offers.

4. Planning

4.1. Network architecture

After it was decided to deploy a converged video and data Remote PHY in the Stofa network, the focus shifted towards crafting the right design that will provide the benefits of R-PHY, and match the Stofa network and requirements.

R-PHY comes with new requirements to the IP network. As the remote-PHY architecture is literally separating two physical elements that were previously on the same circuit board, the network has to provide the same stability and fixed low latency for the solution to work over the existing fiber network.

Replacing the classic analog optical equipment means that a lot of focus was put on the transceivers, and not just for the fibers going to the RPDs. As classic headends turn into IP hubs instead, the need for 100/200G backhaul links needs to be addressed. Stofa was also mindful of temperature limits for the transceivers going into the RPD's.

For the actual design approach – there is no "one size fits all", as optical network design will vary from operator to operator. The following briefly describes the design variants Stofa evaluated.

As previously described, Stofa has many headends in rural areas, typically with a very limited number of fibers connecting them to the central network. In order to select the optimal network architecture, Stofa chose one topology representing a geographic area that includes typical headend sizes and distances between them, as described in Figure 8.

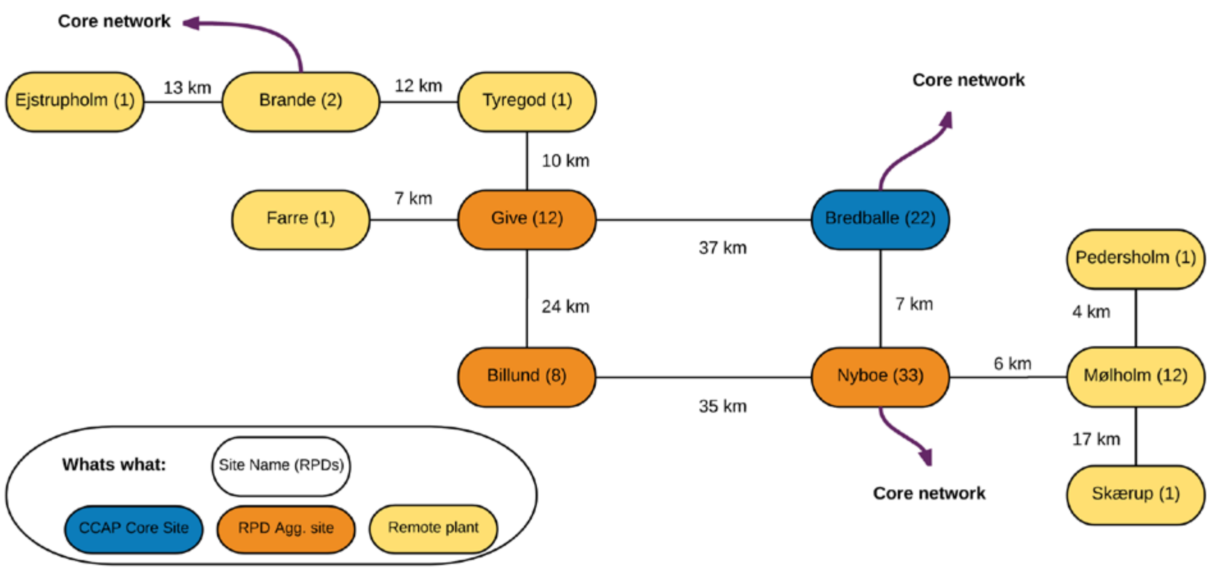


Figure 8 - Stofa Selected Reference Area

4.2. Planning the fiber and interconnect network

Stofa reviewed various options for interconnecting the elements of their network design, as detailed in the section below.

Stofa considered upgrading the existing Point-to-Point fiber network to a DWDM network in order to connect the RPDs to aggregation sites where the MAC cores reside, as described in Figure 9.

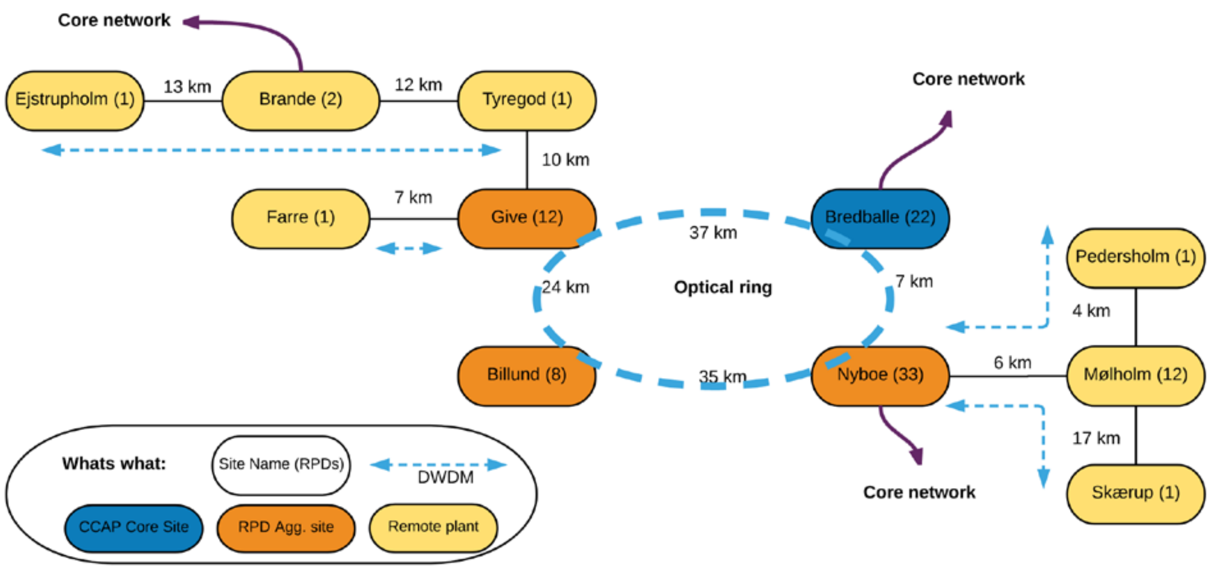


Figure 9 - Reference Area with DWDM Solution

A clear benefit of this approach is that active equipment (including everything belonging to the IP network) could be consolidated to fewer headends. This consolidation also means less investment in costly 100G/200G backhaul transceivers as each 10G RPD link uses a dedicated 10G wavelength over DWDM using 10G DWDM transceivers in both ends. One last benefit is that using DWDM won't drastically change the day to day operations of fiber plant and nodes.

However, many challenges were identified as well. As Stofa has limited fiber between the existing headends, a 50 GHz / 80 Channel DWDM system would be needed in most areas, and in some cases even 80 channels would not suffice (where more than 80 RPDs each using one DWDM Channel, needed transport across a single set of fibers). The range of the DWDM transceivers would also be problematic in some rural areas, requiring optical amplification at some sites that were initially designed as passive sites. On top of all that, the complexities of ensuring redundancy in the DWDM network and the much higher cost of DWDM transceivers compared to 10G Long Reach (LR) optics were additional concerns for Stofa.

Hence, the DWDM solution was not an ideal fit for Stofa. The next logical approach would have been to design a single-service network to support just the RPDs. In a layer 2 (switched) design, guaranteeing low latency and symmetrical traffic flows in the network is relatively simple. Operators have to deal with the known limitations of layer 2 networks, like the number of supported VLANs, spanning-tree for redundancy etc. Nevertheless, this approach is feasible.

Despite its benefits, a layer 2 (L2) network was not considered as there are some serious downsides. Stofa, like many other operators, is going to be using the converged interconnect network (CIN) for other services as well, making it impossible or overly-complicated to use L2 in practice. For L2, an operator may even need to build this as a completely isolated network – not benefiting the rest of the business.

Another strong argument against the use of an L2 network in the Stofa network was the following. With DAA, an operator will be aggregating IP traffic where their fiber infrastructure is aggregated. This leads to physical sites with massive backhaul capacity requirements and that is probably the biggest downside of deploying DAA over L2 networks – an operator will likely need a lot of expensive 100G+ transceivers that will be poorly utilized in an L2 network since effective load balancing of IP traffic requires IP routing which in turn requires a L3 based network.

For Stofa the preferred design option was a converged IP (L3) network that supports all existing services and fulfills the requirements for R-PHY. Being an early adopter, this did not leave Stofa with many options other than to study roadmaps and choose the best future solution that complies with the network requirements (Further details of CIN design in a later section).

4.3. RF Plant Upgrade and Updating Network Inventory System

Stofa decided, as part of the DAA transformation to also migrate the HFC network to 1.2 GHz Downstream/ 204 MHz Upstream operation– a necessary move to be able to offer symmetrical services and to prolong the lifetime of the initial R-PHY rollout. On the pre-existing HFC network, Stofa had limited topology data linking cable modems, taps, amplifiers, and nodes. A key goal for the HFC rebuild was to improve topology data for the RF network.

This was to allow better integration with monitoring and PNM solutions in order to allow Stofa to perform targeted proactive network maintenance, and to be able to automatically identify affected customers during outages.

It was decided to do the HFC rebuild in 3 phases on a per service group (SG) basis:

A. During the first phase a SG is redesigned, resulting in updated and accurate network documentation. No site surveys are done yet (unless known issues are present). Some, but not all, inconsistencies in the network documentation are found and fixed at this point. The updated design data is automatically imported into the PNM solution to enable use of the PNM tools to troubleshoot issues after phase 3.
B. During the second phase a SG has its passives and amplifiers replaced, still keeping the original US/DS split. Quality Assurance during this phase means that service groups are deployed with identical components, guidelines for mounting, cabling etc. Any inconsistencies between the new network design and the real world are captured during this phase and scheduled for field fix. In addition, cabinets are checked for defects and improvements needed for better airflow. As the new Node/RPD generates more heat than the old optical node the cabinet is given a new lid and door – both with ventilation holes. A small improvement that yields a 10-15C temperature decrease in the Node/RPD. After phase 2 the HFC network is completely rebuilt (but using the old nodes and frequency plans).
C. The third and final phase involves deploying the R-PHY device/Node and swapping diplex filters and upstream modules in the amplifiers, as well as changing the split to 1DS-1US. A new frequency plan is effectively in operation as soon as the RPD is online. RF filters on each tap are swapped to reflect the new frequency plan (Broadcast TV subscriptions are managed using bandpass filters).

4.4. CIN planning

DAA brings several specific requirements to the CIN, the Converged IP Network. The solution chosen by Stofa (depicted in Figure 10) is entirely IPv6 based and requires all devices in the CIN to be IPv6 capable (don't assume this is the case). Also, the ability to either support or effectively transport IEEE1588 timing information needed for RPD operation is crucial. Being an early adopter of DAA, there was a very limited choice of possible switches and routers that comply to these requirements. This was made even more challenging because of the requirements for highly scalable backhaul links (nx100G per router). It would have been possible to deploy a cheaper platform based on 40G backhaul links, but the lifetime of such a solution would not be in line with the wish to roll out a platform with a very long lifetime in the field and network.

Stofa decided to build a multi-service IP/MPLS network to serve as the CIN. A key driver for this was the wish for full flexibility on the association of RPDs to MAC cores, and removing any geographical constraints. Ideally, the ability to simply move RPDs (through provisioning) to a new core would also mean that transitioning to a virtual core at a later stage would be seamless.

The wish to implement (and provide device support for) 802.11X and MAC SEC should be carefully considered. For 802.11X specifically, there are challenges if RPDs are deployed in Daisy Chain or Ring Topologies; we have noticed 802.11X vendor implementations may be pre-mature. It is recommended that the CIN edge devices used to support the implementation be compatible with those recommended and tested by the RPD vendor.

Another observation: for the near future – we expect the backhaul links to be a major cost driver- especially if deploying 100G/200G. The Cable Labs Coherent Optics specification [P2PCO-SP] could help drive costs down though.

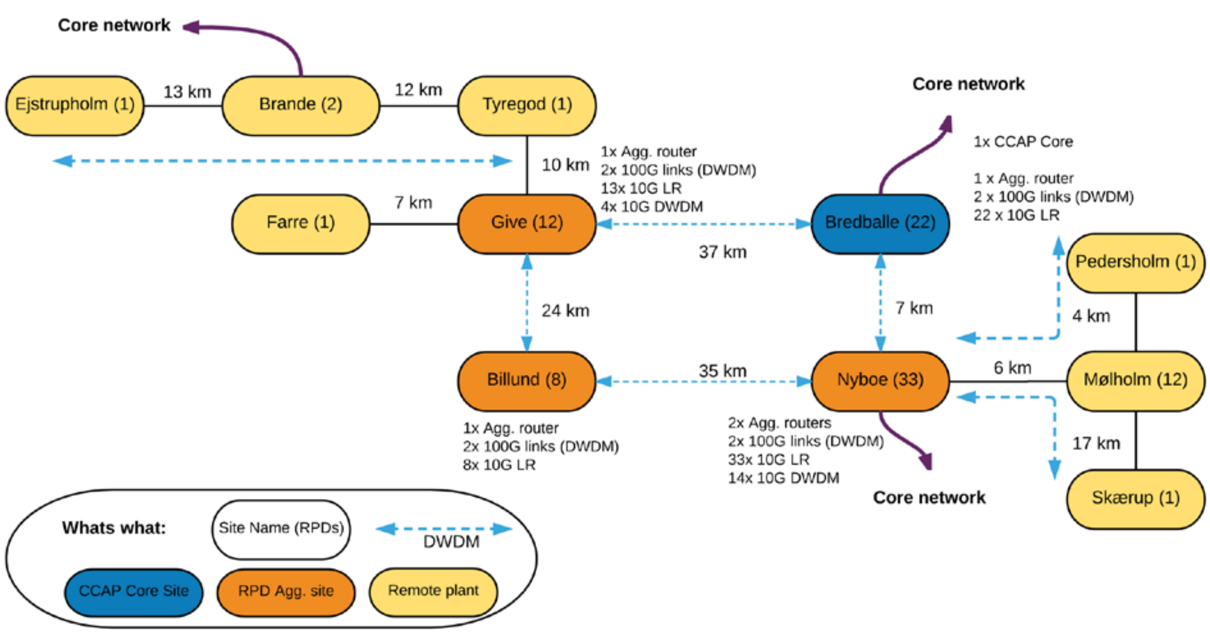


Figure 10 - CIN Network Design

4.5. IEEE1588 Timing

The implementation of Precision Time Protocol (PTP) Grandmasters (GM) and supporting the flow of PTP traffic in the network was originally a major concern for Stofa as there was no in-house knowledge of IEEE1588. Stofa limited its lab tests to GM devices from two vendors and the experience from using both was that the basic PTP functionality needed for DAA is almost trivial. If selected CIN devices can provide consistent low latency forwarding ideally using QoS based on DSCP classification, the operator only needs to consider possible asymmetric routing for the PTP traffic – the reason for this is illustrated in Figure 11:

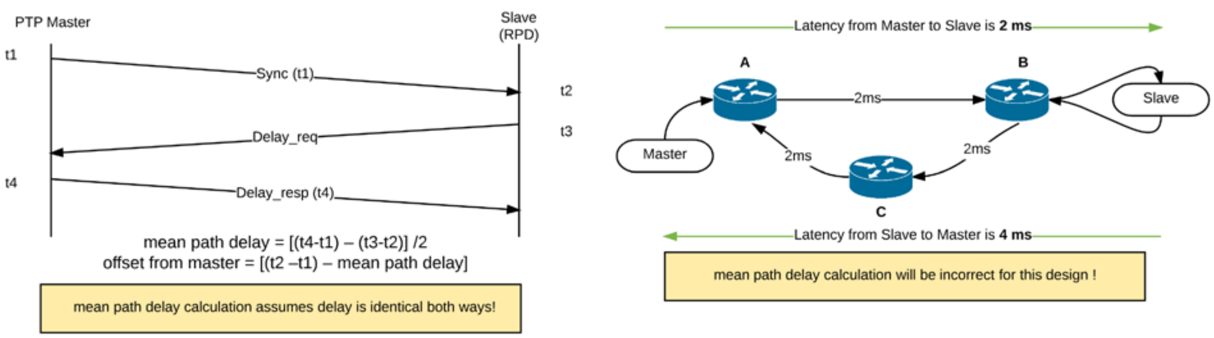


Figure 11 -PTP Latency Calculation

PTP used with Remote-Phy allows for a packet delay variation (PDV) of 2 ms – which means that R-PHY should actually work with up to 2 ms of difference in latency in an asymmetric routing situation. But with more focus being put on Latency in DOCSIS networks Stofa has decided to aim for symmetrical routing for PTP – to be able to implement any latency improvements done to DOCSIS without having to rework the CIN.

Failover of PTP in case of GM failure or network issues is still very loosely defined in the R-PHY specs and recovery implementations vary from vendor to vendor. Currently with the Stofa implementation (depicted in Figure 12), the workaround is to have two active GMs in the network sourcing the PTP traffic from the same IPv6 address but using different prefix lengths. In effect this means that the IP routing protocols makes the primary GM reachable on the network until the link to it fails, in which case the routing protocol switches to the secondary GM. This does not account for cases where only PTP communications with the GM fails – In these cases manual intervention is needed but with the holdover time for the MAC core and RPDs of at least 2 hours, this is tolerable.

The Stofa CIN network is actually license-based upgradeable to PTP Boundary clock support. It remains to be seen if this step will be needed in the future. So far Stofa have not needed PTP test equipment to validate accuracy in the field, because of the low IP hop count in the network, and simplified routes to the RPDs. However it is important to understand that the operator will need test equipment synchronized to the same source as their GMs (typically GNSS) to measure and troubleshoot timing accuracy, for more complicated networks, and for better analysis of the impact on PTP accuracy as it traverses the network.

As more experience is gained Stofa expects to increase both distance and hop count between CCAP cores and RPDs – a handheld PTP reference might prove very useful at that stage.

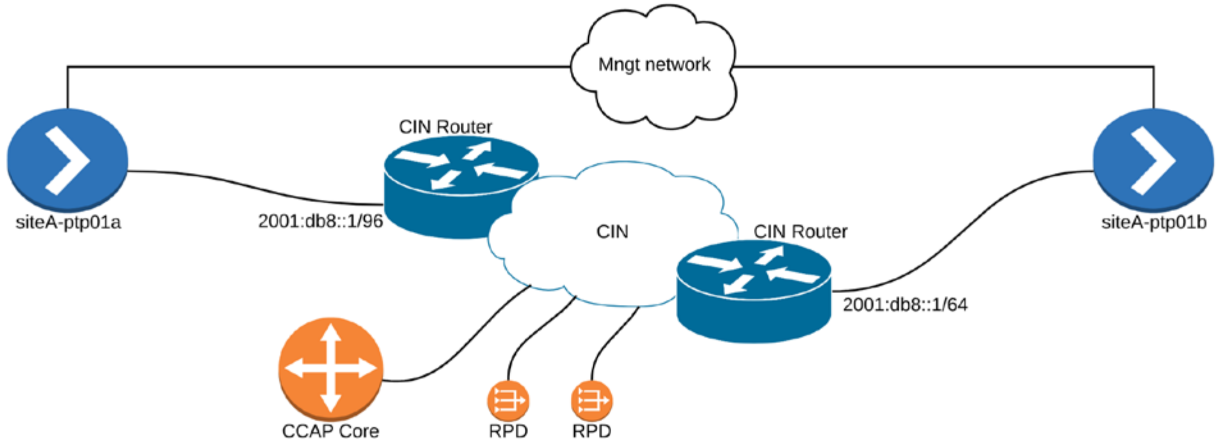


Figure 12 - Timing Distribution Network

4.6. Product Qualification Phases

4.6.1. Initial Testing and Solution Evaluation

As mentioned, Stofa is an early adopter, and was one of the first operators in the world to qualify and deploy a Remote PHY architecture with live customers. Correspondingly, the first MAC core and nodes that were used in the initial testing in the Stofa lab were of the first few beta units of the product worldwide. Those components had to be integrated with a new DHCPv6 and timing servers, and new routers chosen for the CIN of the R-PHY network. Given all that, Stofa wanted to be best prepared for the testing, and started as early as the equipment vendor could allow them to test.

In order to get a head-start on the new R-PHY technology, Stofa received a very early pre-production unit into their lab many months before it was ready for production.

As a preparation phase, Stofa decided to test the integrated CCAP solution in the lab, although the solution they are planning to deploy is Remote PHY and not an I-CCAP solution. The rationale for that was that the hardware used for the MAC core operation was the same as the I-CCAP hardware, and the CLI commands and general flow of operation are the same between the I-CCAP and the MAC core solutions. Stofa tested the I-CCAP in the lab, and they also launched a limited field trial with the I-CCAP, in order to learn more about the field behavior of the platform and ability to converge DOCSIS and VOD video services. The lab and field trials gave the engineering and operation teams some experience with services configuration, monitoring, and debug of the platform. After this trial Stofa gained valuable experience and confidence on the Remote PHY architecture.

The RPD and node were staged in the Stofa lab and connected in a very basic network scheme to make it operational, as depicted in Figure 13.

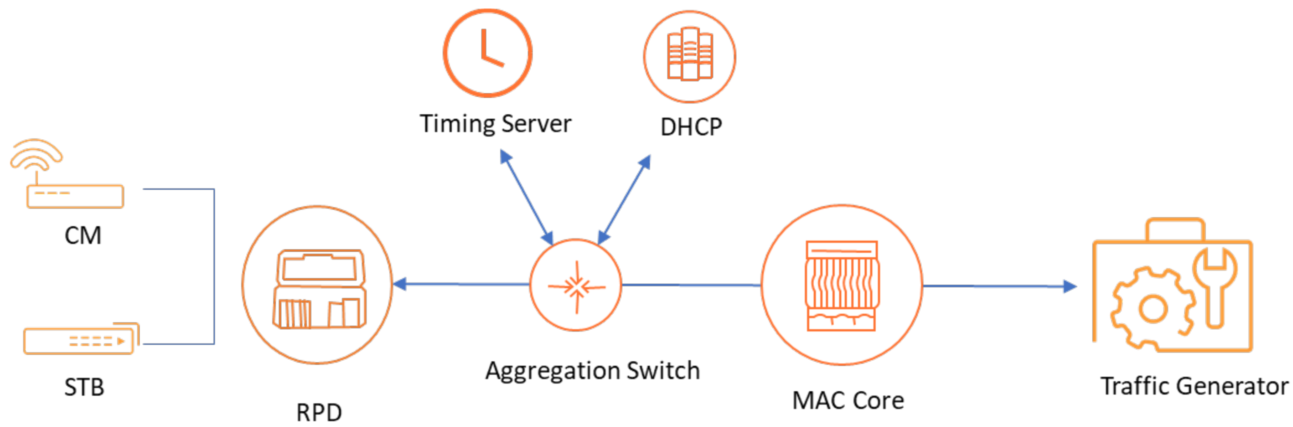


Figure 13 - Stofa Initial Lab Setup

The test plan that was run on the set up including the following tests of functionality:

A. Node registration in the MAC core – GCP tunnel established, timing server connectivity operational
B. DOCSIS – cable modem registered, high throughput achieved to CM
C. Voice over DOCSIS
D. Video on Demand (VoD) services
E. Broadcast Video
F. DOCSIS 3.1 DS – OFDM
G. Multiple R-PHY nodes on single core
H. Routing – IPv6
I. Routing – OSPF and OSPFv3 operation
J. Terminal Access Controller Access-Control System (TACACS)
K. Lawful intercept using SNMPv3
L. Load testing, making sure QoS is maintained, US and DS
M. DOCSIS Load Balancing – making sure load balancing rules are triggers are respected
N. Integrated Upstream Agility (Dynamic Modulation Profile switching)
O. Sparing – Routing Switch Module, Downstream card, Upstream card
P. Link redundancy – to the Remote PHY module
Q. Timing server failure – connectivity lost to the timing server, testing the holdover operation

Additional tests were run in later phases that included more than one RPD per core, and additional error cases coverage.

4.6.2. Integration into the Network

The new R-PHY product must fit into the existing operator's network and be able to integrate with existing components that are part of the normal network operation and management. The integration with these components had to be tested in advance, and guiding documents generated in order to instruct the operational team during deployment.

The main systems that required integration are:

- **DHCP servers** – Following internal analysis, and also aligning with the vendor recommendation, Stofa decided to use separate DHCP servers for the RPD nodes in the network. It made sense separating the DHCP instance from the one used for subscriber devices and maintain separation of services for the sake of security and ease of operation. The DHCP servers selected had to be IPv6 supporting, to match the core and node routing capabilities. The new DHCP servers were set up in the lab with the R-PHY devices and tested with the rest of the architecture for the first time.
- **TACACS Server –** Stofa manages their users and permission levels using TACACS servers, the core had to be tested along with the existing servers.
- **Proactive Network Management** Solution – in order to improve network visibility and allow fast action to handle potential customer affecting issues, Stofa decided to adopt a new network management system, which made integration testing much easier, given the R-PHY and PNM products came from the same vendor. The PNM solution chosen collects information from the plant, alerts the operator of a proactive alarm notifications which allows them to fix it before it is causing any significant service degradation and or outage to the customer. More details and case studies can be found in [Cunha PNM].

  Below in Figure 14 is a visualization of the topological information provided by the tool, allowing for geographical location of potential outage causing issues.

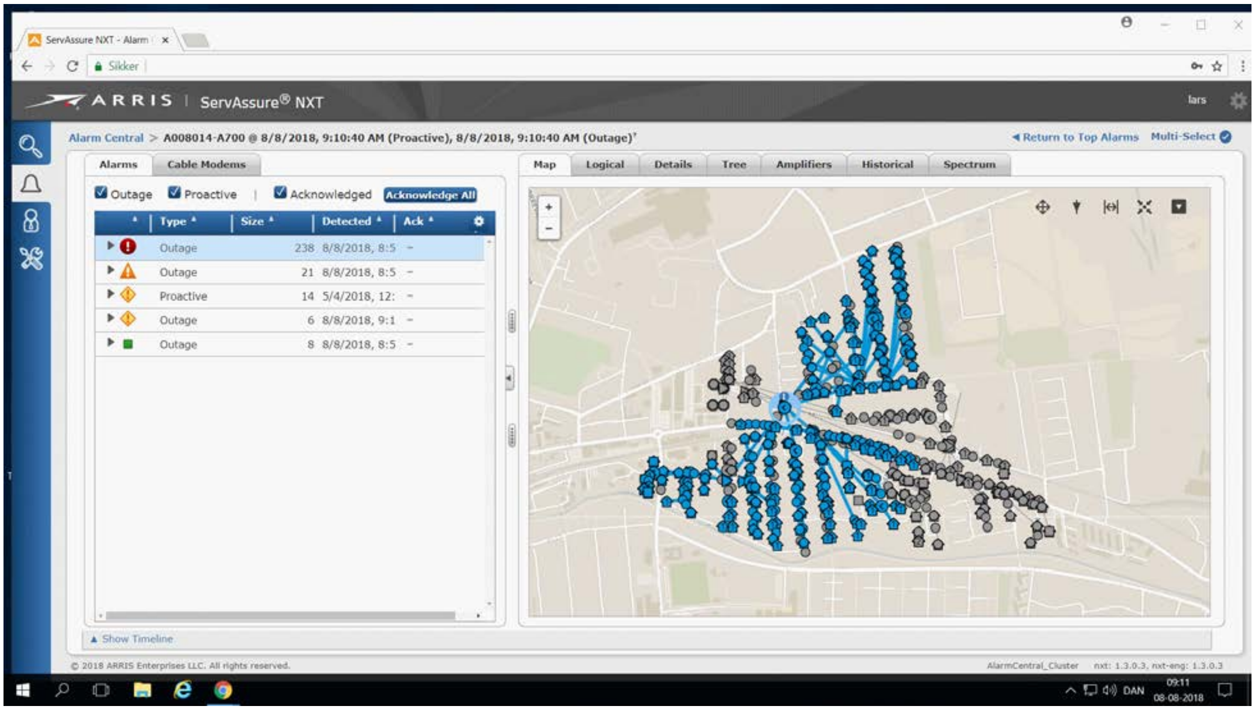


Figure 14 - PNM Topology View

- **US RF network alignment and RF Quality Monitoring Solution** – With the analog links becoming digital links between the node and hub, a replacement solution was required for the legacy analog US RF alignment and RF monitoring systems including some of the field tools. Stofa decided to use a tool that connects remotely to the RPD and provides real time US RF spectrum measurements through which the US path can be aligned, and which can be used for periodic or reactive RF network monitoring and maintenance. This tool is measuring the upstream RF spectrum:

- Utilizing Fast Fourier Transform (FFT) data from the RF burst receiver, spectrum from a specific DOCSIS upstream is displayed (Power Density vs. Frequency)
- Uses the FFT data to measure the noise level in the upstream channel

Example screens are shown in Figure 15.

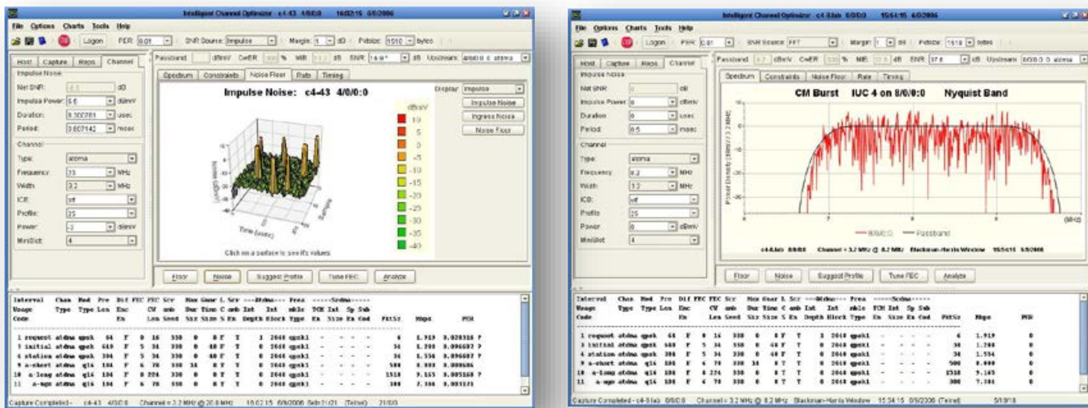


Figure 15 -Software Tool for US RF Network Alignment and Monitoring

- **Implementation of an Optimized R-PHY node RF specification enabling a seamless integration of the R-PHY node with a N+5 RF cascade** – With support from Stofa, the vendor defined the D3.0 and D3.1 RF performance and level design for the R-PHY node with RF cascade to achieve a most optimized EOL (End of Line) MER supporting 4K QAM Downstream and 2K QAM Upstream operation.

4.7. Automation

The introduction of Remote PHY architecture requires a significant upgrade of the network operational management. Distributed Access Architectures drive more functionality closer to the subscriber and into the field. This causes an explosion of managed devices out in the field. In locations where there were only analog components, now with DAA there are a few hundred more digital and managed devices. The Remote PHY devices are IP devices that are part of the IP network, require software upgrades, and may suffer logical and physical outages. All this strongly drives the need for more automation in the network, for onboarding, provisioning, and monitoring those RPDs.

If we summarize the different functions in the back office that need to be managed and integrated to support the operation of the R-PHY devices, it may look like this, in Figure 16:

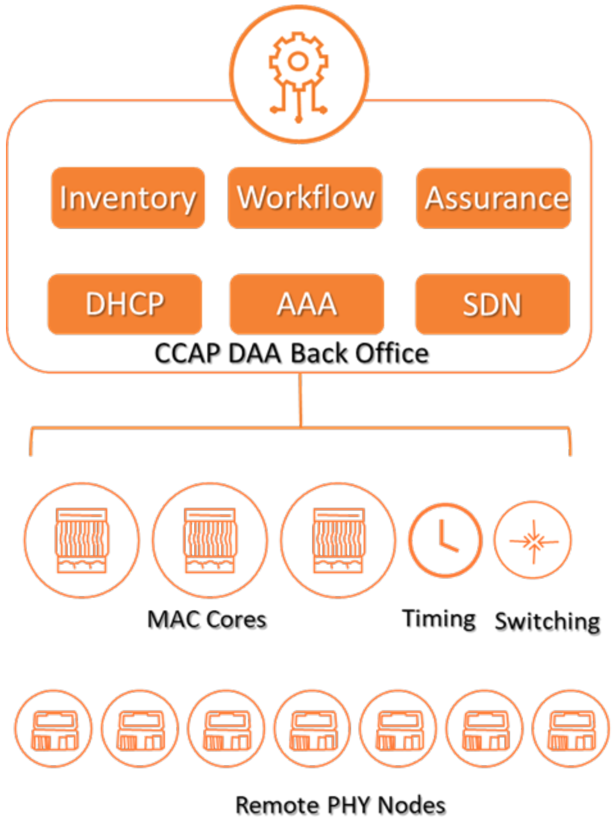


Figure 16 - Back office Management Architecture

Stofa considered different options for managing the network, including building their own automation tools, but decided it will be more beneficial to invest in a long-term management system for the network that can expand to additional functions and support future migration to virtualization.

Specifically, Stofa decided to deploy an RPD manager, which supports automation of the onboarding of a new node. It performs this function from the box into the network, with configuration required from the operator's side. This is very critical to operators like Stofa that are planning to deploy dozens of RPDs a week (or more) as part of a fast roll out plan or are needing to manage a large RPD deployment.

The RPD manager allows the field technician to scan the barcode on the RPD using their mobile device at the point of deployment, and loading that information into the centralized database, to create the network inventory. This information will include the RPD serial number, the node geo-location, time of day, and more parameters relevant for the node installation.

After the node is identified, it is matched to a MAC core (according to the operator's policy), and downloaded software version and initial configuration.

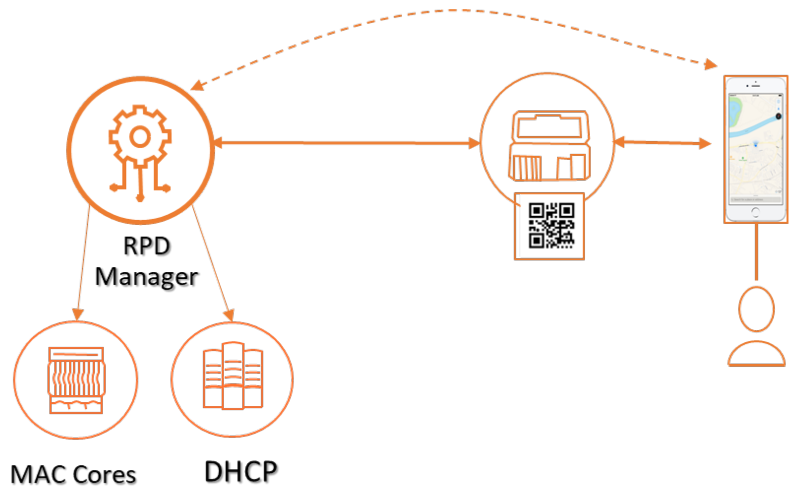


Figure 17 - RPD Manager Onboarding

In order to manage the matching of RPDs to cores, the RPD manager interfaces to the DHCP server for the Remote PHY devices. It is also able to download configuration templates to the MAC cores, to eliminate time-consuming manual CLI commands.

Automating the RPD management allows the operator to do bulk software upgrade or configuration changes, thus reducing the cycles and manual work required to manage the field devices. Its operation diagram is included in Figure 17.

In the future, the same network management system is planned to also support the provisioning of the CIN, allowing for end to end provisioning and monitoring of the Remote PHY network, from one single system.

5. Deployment and Operational Results

5.1. Field Deployment

With the objective to start the first field trial, the lab setup was replicated into a field location with 4 RPDs connected to the MAC core. The first trial phase included launching only one RPD into the live network, supporting DOCSIS, VoD and Broadcast services to live customers. The first node was, naturally, the one that took the most time and effort. The dominant challenges encountered were mostly found in the deployment of the "supporting network", and were mostly related to routing configuration. The routes to DHCP and TACACS servers had to be established and verified. The new CIN network had to be configured to match the future services expansion, which also took some time and effort. Eventually, the cut over was declared a success, with no issues on the network.

The single node was left running for a few weeks, to make sure all services had good stability. After few weeks, 3 more nodes were cut over, with no issues at the time of the migration or after it.

The field trial was considered a huge success with practically no issues encountered for more than a month despite using pre-production software– and eventually the full production deployment was started as the vendor released field mature software.

6. Performance Improvement

6.1. RF performance

RF Signal data was captured before and after the 3 deployment phases described above. In this table, we summarized the difference in average US and DS signal to noise levels.
DS noise was measured and reported by the cable modem, US noise was collected from the R-PHY node, as described in Table 2:

Table 2 - Upstream and Downstream SNR Measurements

	Upstream average dB				**Downstream average dB**		
	Before	After	Change		Before	After	Change
Min	28,0	31,1	**-0,8**		37,6	35,3	**-3,5**
Avg	**33,6**	**36,2**	**2,5**		**40,4**	**40,3**	**-0,2**
Max	37,4	37,7	**8,2**		42,0	41,8	**2,1**

The US SNR shows an average 2.5dB improvement, with up to 8.2dB improvement in some areas. This will allow Stofa to go to higher D3.1 modulations in the future, and provide higher US capacity to their subscriber.

We note that mild improvement to downstream signal quality is seen, on the average.

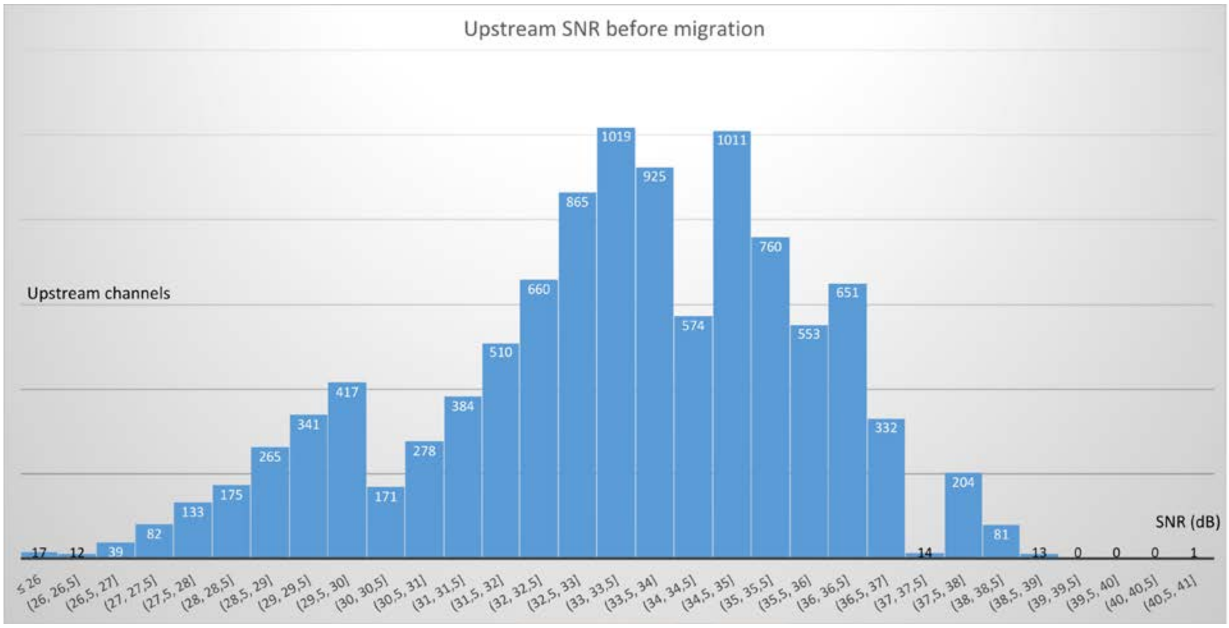
There are few possible causes for this:

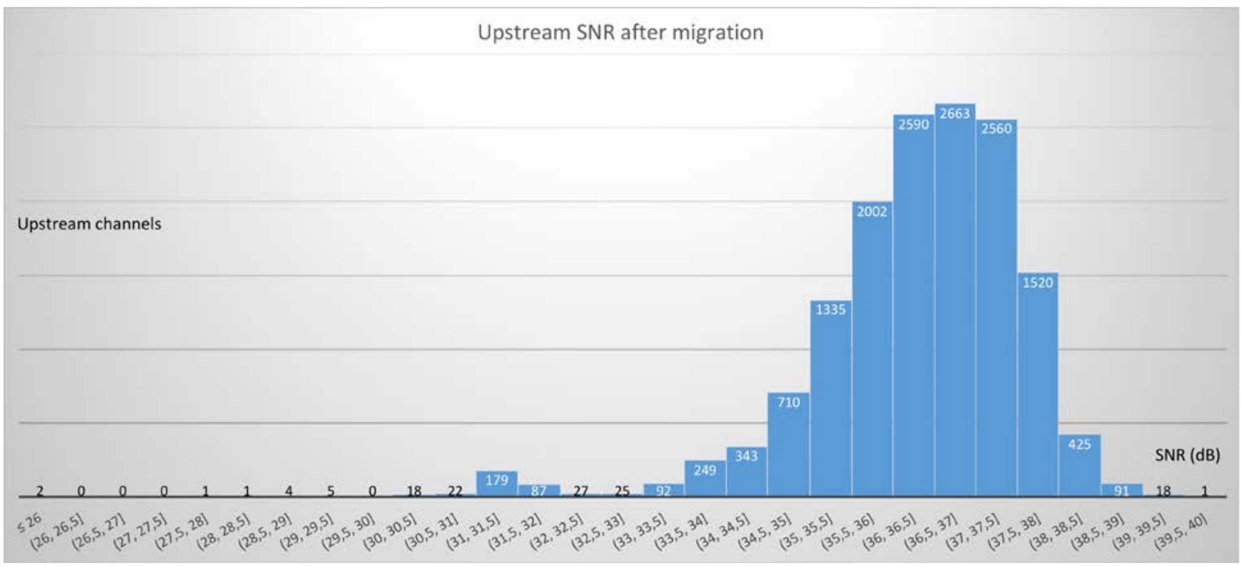
A. A decision was taken to move the DOCSIS spectrum to 722 – 906 MHz, from 218 – 338 MHz. This was done to keep DVB-C video multiplexes clear of possibly impacting LTE ingress noise. In the long run this spectrum will be used for OFDM which is more resilient to LTE interference. The fact that similar SNR was maintained on a much higher frequency range can be considered as an improvement in the network operation, compared to previous state.
B. It should be noted that no changes to the RF drop cable were made except for F-connector replacements (if deemed necessary following visual screening). In many cases the RF drop cables have been out in the network for over 20 to 30 years whilst exposed to varying environmental conditions (low and high temperatures, rain, wind and sun) and possibly mechanical stress (installation conditions). All are factors impacting the RF attenuation loss and RF shielding quality between the tap and home, especially in the higher downstream frequency ranges (750 to 1.2GHz).
C. Deployment of new 1.2GHz R-PHY nodes, RF amplifiers and RF passives follow a strict and highly optimized RF network design and implementation process. RF network (R-PHY node to tap RF outlet) design characteristics assume low drop cable attenuation and cable quality conditions. In cases where non-typical drop cable RF losses had to be compensated, Stofa had historically implemented one-off work around solutions (such as higher RF amp output,

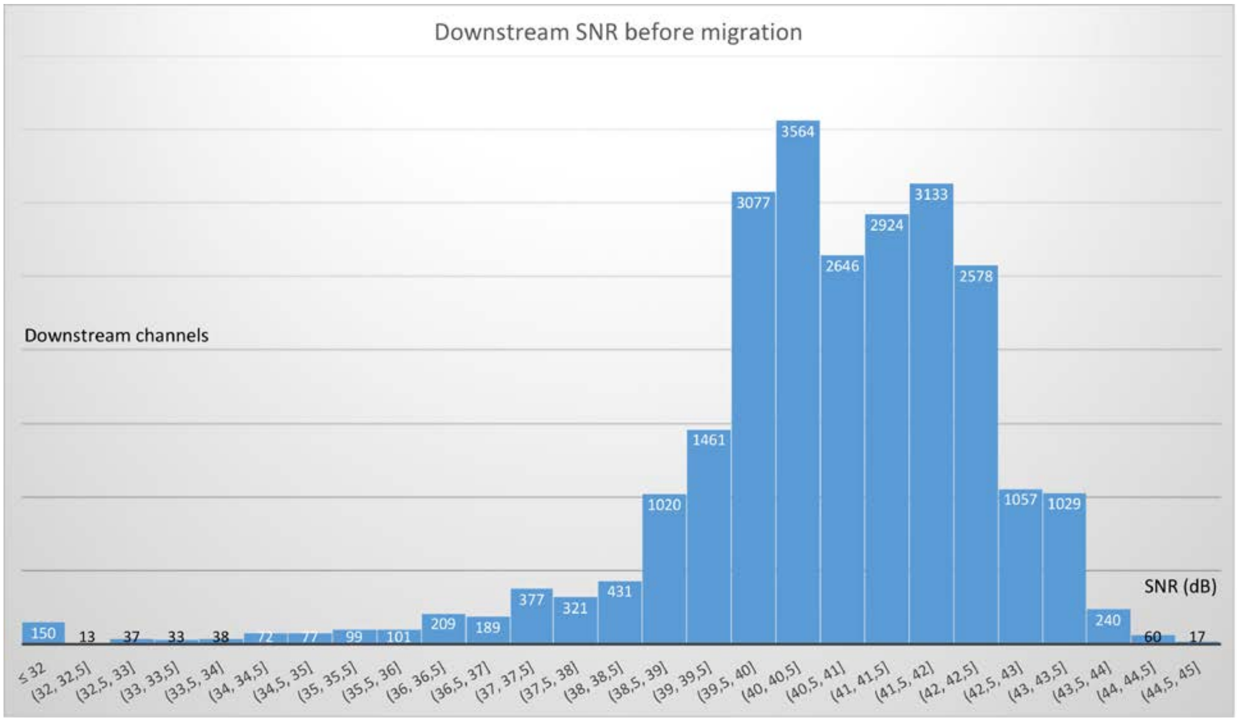
installation of a lower tap value, etc…). Some of these one-off compensation fixes may be negated through the RF network upgrade process.

D. Impact of poor in home RF network quality on End-of-Line downstream performance. Any network changes/RF performance improvements within the home were deemed out of scope for the R-PHY and D3.1 network upgrade project.

The graphs below in Figure 18 show the channel SNR distribution, before and after the network upgrade.


Upstream SNR before migration
Upstream channels
SNR (dB)
17 12 39 82 133 175 265 341 417 171 278 384 510 660 865 1019 925 574 1011 760 553 651 332 14 204 81 13 0 0 0 1


Upstream SNR after migration
Upstream channels
SNR (dB)
2 0 0 0 1 1 4 5 0 18 22 179 87 27 25 92 249 343 710 1335 2002 2590 2663 2560 1520 425 91 18 1



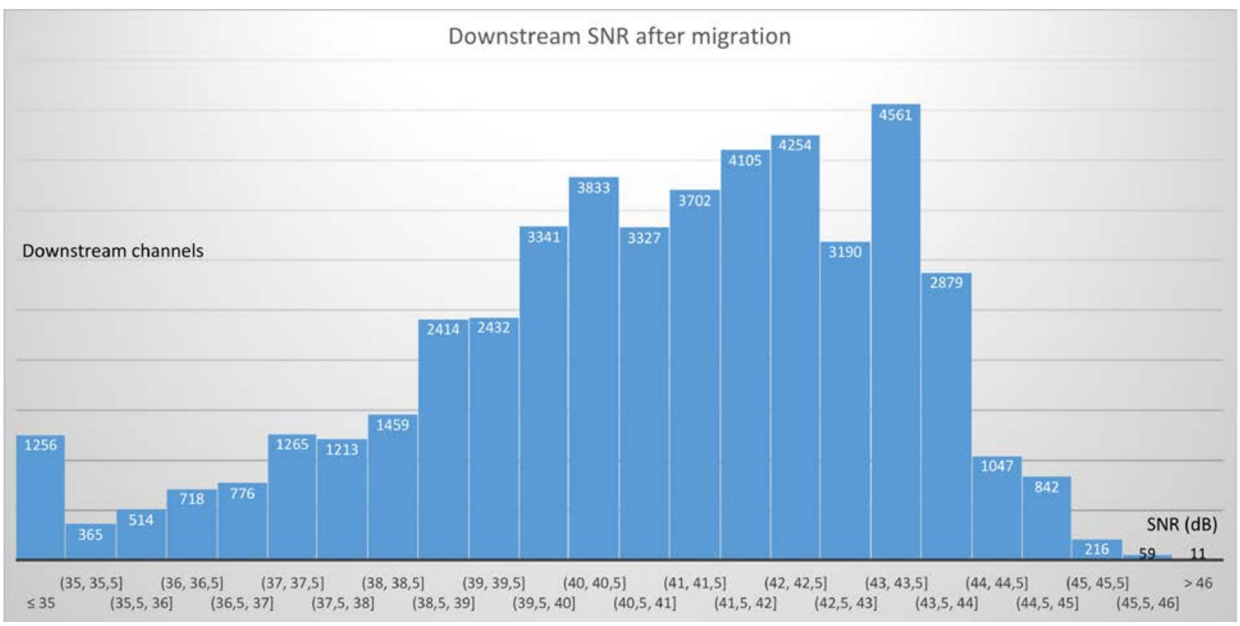


Figure 18 - US and DS channel SNR distribution

In these diagrams we can see in more detail the SNR levels reported for every channel (SC-QAM) that is in use by Cable Modems in the examined part of the network.
Here we can see the clear improvement in US SNR. The DS SNR remains distributed, and is assumed to be as such from the reasons mentioned in the section above.

6.2. Space & Power in the Headend

One of the main drivers for the network upgrade project has been to reduce the space and power needed in the headends for network operation.

Before the network upgrade, the following list of devices were required to provide the full set of services, DOCSIS, VoD and Broadcast, in the headend:

A. CMTS – supporting all DOCSIS services
B. Edge QAM (since using an M-CMTS architecture) – supporting DOCSIS PHY and VoD
C. Broadcast Edge QAM
D. DTI server

Additional headend equipment required is the RF combining network – including RF combiners and splitters to combine the different RF outputs from the EQAMs for unicast and broadcast traffic. Operator will also need optical transceivers to transmit the analog RF signals over the fiber to the nodes. In some operators' network, there is also an RF Switch attached to the CMTS, it was not used in this case.

In some limited cases, Stofa placed the EQAM devices in the hub, closer to the subscriber. We will focus on the more typical deployment scenario where all equipment is deployed in the same headend.

The devices that will reside in the headend in the newly established R-PHY architecture are:

A. MAC Core
B. Timing servers
C. Aggregation Router(s)

A note about the aggregation routers: the switches or routers that are required to transmit the R-PHY signals from the MAC core to the nodes can reside in the headend, data center, or hub. In many cases, some of the routing devices were already pre-existing in the headend before or are used for other network services. In our analysis, we have chosen to include one additional "dedicated" aggregation router for the sake of comparison to the previous state of network devices in the headend.

For Remote PHY, given the decentralized nature of the architecture, PHY functions are distributed in the field, inside cabinets (in the Stofa case), or field nodes (on a pole or in storage locations). Those devices take space, naturally, but that space is assumed to already "be there" given the fiber node that is enclosing the Remote PHY device was there for the legacy services, to provide analog fiber transmission. In some cases, there may be a need to upgrade the fiber nodes or their power supplies to meet the new R-PHY requirements. These upgrades will incur cost and resources that are not calculated in this section, given they are outside the headend, and may not be applicable to all operators.

Summarizing the space and power consumption for all the devices that combine the two configurations, assuming power consumption at 25^0 C and calculating the amount of space and power required to make 96 SGs operational, the numbers are given in Table 3:

Table 3 - Space and Power required for M-CMTS and R-PHY Devices in the Headend

Device	Count	Space per Unit [RU]	Estimated Total Power [W]
CMTS – UBR 10K	2	18	4470
EQAM – DOCSIS and VoD	2	13	3000
EQAM – Broadcast	1	1	400
DTI server	1	1	80
E6000 MAC Core	1	16	3125
Timing Server	2	1	40
Aggregation Router	1	1	320

It is important to mention that the R-PHY solution can double and more its capacity without any additional hardware required. We have chosen to run the comparison on 96 SGs, since we feel this is representative enough, and in addition, the lower density on the legacy devices makes the numbers for higher capacity very difficult to support within one hub.

If we combine those numbers for the case of 96 SGs support, we get the totals in Table 4:

Table 4 - Summary of Space and Power Required for Legacy and R-PHY Architectures

	Space [RU]	Power [W]
Legacy Architecture	64	7950
Remote PHY	19	3485
Improvement	Over 3x	over 2x

The difference in space and power consumption between the "before" and "after" states is quite outstanding.

However, we should consider a few points that may narrow the gap a bit, but would still keep the obvious benefit of the transition to R-PHY:

- The legacy architecture Stofa started with was in service for many years, and included older types of devices, that may have not taken advantage of more current technology advancements such as newer chipsets, and routing technologies. It is safe to say that there are newer I-CCAP solutions in the market that will be better than the M-CMTS architecture in terms of space and power. However, even those alternatives come short when compared to Remote PHY, simply because R-PHY moves the PHY processing out of the headend and thus removes space and power required for it.

- Stofa has been using M-CMTS architecture that required a few more devices such as the timing server, and a separate EQAM. If the starting point has been I-CMTS or I-CCAP, it is safe to assume that the initial space and power consumption would have been lower. In addition, in order to support redundancy, external RF switches have been in use. Again, there were alternatives in the market that supported that sparing protection without the need for external devices, and with lower space and power consumption.
- The legacy architecture included external Broadcast QAM processing – there are solutions in the market that already allow for that processing to be done inside the CCAP chassis, thus reducing the need for that EQAM.

As mentioned, even considering all the points that may narrow the gap between the legacy architecture and the Remote PHY architecture, the new design provides significant space and power savings in the headend.

The benefit becomes even more evident when we consider that the existing devices used in the headend for the MAC core processing can double or more their capacity, supporting few times more the number of service groups estimated in this analysis, without any additional hardware component needed.

In the future, the MAC core function can be virtualized, meaning transferred to reside on a virtual machine, using an off the shelf server. Depending on the performance of future off the shelf servers versus future appliance-based MAC Cores, it is possible that this may provide even greater space and power savings, as well as increase the network resource assignment flexibility.

6.3. Operational Simplification

The new network architecture introduces better operational simplification, compared to the previous network Stofa was managing.

If we look at the number of headend devices that need to be managed to support 200 service groups, we can see the significant difference in Table 5:

Table 5 - Number of Managed Devices in Different Architectures

Before Network Upgrade	After R-PHY Introduction
4 CMTS	1 MAC Core
3 Universal Edge QAM	2 timing server
1 DTI servers	1 Aggregation Router*
8 devices	**4 devices**

Note - the number of additional aggregation routers depends on the operator's architecture

Less devices that need to be managed means operational simplicity: fewer physical devices mean less network cables and interfaces to manage them. It also means fewer management tools (software UI or command line) need to be used and trained for (which will also lower the support cost). It also means less interoperability issues between the devices, and quicker debugging process (since there are less devices to check for the source of issue). It also means less IP addresses need to be assigned and less inventory the operator will have to keep in order to deal with outages.

In the remote PHY architecture, all the nodes are managed and provisioned through the MAC Core, per the R-PHY Spec [R-PHY Spec] (there is no direct configuration interface into the remote PHY devices). So although R-PHY introduces many new devices into the field, they are all provisioned and managed from one central point, which makes it easier from an operational perspective, and also for problem diagnosis.

According to technicians' feedback from Stofa, understanding and operating the new architecture was significantly easier compared to the previous one, due to the centralized management. It required less training, and shortened the debug cycles for issues in the lab and in the field, compared to the previous network architecture.

The additional level of automation provided by the RPD manager tool helped a lot to facilitate the quick and painless installation process. The RPD manager allowed to shorten the new node deployment period from roughly 15 minutes on the legacy platform to just 5 minutes on the DAA platform (including scripted CIN, DNS and IPAM provisioning currently done outside of RPD manager) – While this might not sound like a huge improvement - it is a critical optimization when deploying dozens of RPD’s each day.

Conclusion

Key Benefits

Stofa gained many benefits out of the network upgrade project and the transition to R-PHY.

These are the ones that were most important to Stofa, covered in this paper:

- **Better Signal to Noise Ratio (SNR)** – as measured, the transition to Remote PHY provided significant increase in US SNR (average of 2.5dB). The improvement of SNR on the DS direction is not manifested in the measurements. We do believe there is some slight improvement that is countered by the transition to the higher frequency range. In addition, there is a potential DS SNR improvement that is limited by other elements in the existing network that have not been upgraded such as the drop cable and in-home end-of-line network.
- **Path to efficient use of DOCSIS 3.1**– the network upgrade project included all devices upgrade to 1.2 GHz spectrum support in the downstream. This enlarges the available downstream spectrum for transmission, using DOCSIS 3.1 above the 1 GHz previous top bar. It also allows upstream high split, of 204 MHz. In addition, the SNR increase in both US and DS directions allow for higher modulation orders to be used for signal transmission, hence allowing more bits per Hertz on the existing infrastructure. These changes significantly increase the plant capacity, and allow Stofa to increase their bandwidth service tiers offered to their customers.
- **Space and power saving in the headend** – the space and power needed to support the R-PHY architecture in the headend was shown to be significantly lower than the previously used architecture – 3x saving in the space required, and more than 2x saving in power, for the same amount of service groups. The saving is very impactful in terms of operational cost, and will allow Stofa to consolidate headends and hubs.

- **Future growth made easier** – the Remote PHY solution deployed, as well as the supporting CIN network, were chosen out of consideration of the future Stofa needs. The design was created focusing on future growth, such that additional capacity and capability added to the network will not require field technicians and truck rolls. Future upgrades to the network will be done by remote software configuration, licenses enablement, and capacity increases in software. Stofa fully focused on guaranteeing that, as part of their network planning process, and have invested in resources and tools today, for the network needs of tomorrow.
- **Path to virtualization –** In the selected distributed access architecture, Remote PHY, the MAC core functionality remains in the centralized headend, allowing for better control and access to it. This design will enable migrating that functionality in the future to virtualized servers, performing the same functions, using a virtualized MAC core on off-the-shelf servers. These virtualized MAC cores, or vCores, will be designed according to Network Function Virtualization (NFV) standards, and managed according to Software Defined Networks (SDN) principles, paving the path to a fully virtualized headend design.
- **Improved operational simplicity** – as shown, the network upgrade provided a greater operational simplicity, for engineering teams, support technicians, and customer services. The simplicity is gained along with the decrease on the number of devices to be managed in the network, the centralized management of all the remote PHY devices in the field, and the additional level of automation obtained using advanced PNM and orchestration tools.
- **R-PHY project drove an upgrade to the "DOCSIS supporting network", more investment made in CIN network upgrade** – Along with the access network upgrade, Stofa decided to invest in upgrading their CIN network to be a L3 supporting network. In this design, given everything is routed, Stofa can load share traffic dynamically across all the expensive backhaul links, and not have links dedicated to one service or another. Secondly, with RPDs connected directly to the IP network (using low-cost 10G LR transceivers), they are not locked to a specific MAC Core site, which gives network configuration flexibility as well.

Key Challenges

Such a complex migration project cannot come without challenges, along the way. Some stemmed from the still young technology being used, and some from the significant change this upgrade has made to the network and the operations:

- **Remote PHY Spec stability** – One of the significant challenges in the R-PHY project was derived from Stofa being a very early adopter of the new architecture. During the product development phases, the R-PHY specifications were still changing, which caused delay in product delivery, and some recurring changes in the network design for deployment. Stofa's strategy has been to keep everything standards based so quite a lot of time has been spent discussing how grey areas of the specifications could/should be implemented. Close cooperation with the equipment vendor is and has been key for Stofa to be able to start the rollout at such an early stage.

- **Network planning** – In order to create the best design for the Stofa network, the operator had to investigate new areas for them, such as the CIN routing upgrade, and the timing distribution architecture. Stofa upgraded their routers to support future growth of the services, and thus purchased and integrated new spine and leaf routers, creating a resilient new backbone network. This network also had to support the timing distribution requirements needed for Remote PHY operation, guaranteeing low delay and symmetric forward and return paths for the timing synchronization traffic. This was a new domain for Stofa, in which they needed to ramp up fast, which posed some challenge for the network architects during the project.

- **Operational processes update** – as with every major network upgrade project, the transition to a new architecture required massive updates to the operational processes defined for the Stofa engineers and technicians. Deep level trainings and educational sessions were held to bring the team up to speed on the new architecture and create new processes that will optimize the installation process and network management for all types of services.

- **Change in field measurement tools** – the change of architecture was also accompanied by the need to change some of the measurement and debug tools that were previously used with the M-CMTS network design. Specifically, the RF alignment procedures used in the past were difficult to use with R-PHY, as they required proprietary support in the nodes and headend devices. To resolve that, Stofa have transitioned to standard based methods of data collection from the plant, using DOCSIS standard features (like FFT MIBs) to obtain the SNR and noise values from the plant.

Major Takeaways

For operators considering an upgrade to R-PHY, or getting ready for the deployment, we believe the Stofa story as told in this paper will provide a lot of value, by preparing the operators for the main decision points and activities you will undertake as part of the project. Here are the main points for consideration that we have drawn from our experience:

1. **Start testing early** – getting yourself familiarize with the product and architecture is going to pay off many times over later. Start testing as early as you can, even with similar flavors of the architecture. Getting your lab ready for the new architecture testing is a non-negligible effort, and you will save yourself time if you start that early, even before the product is available.
2. **Planning is key** – one cannot underestimate the importance of pre-planning in a complex project like an architecture upgrade. Planning the lab and field qualification in advance will allow the technicians and network engineers time to figure out their needs to support the effort. In addition, planning the deployment phases in advance will uncover migration challenges, and operational issues that can get resolved in advance, as to not slow down the roll out.
3. **CIN network and Timing architecture are of great importance** – Deploying DAA is massively different than I-CMTS or M-CMTS, and their supporting networks are more complex, specifically the CIN and Timing architectures. Operators must dedicate resources to plan these aspects of the network, with the right experience and skill sets. Specifically, the CIN network has to be designed, as the operator must make sure they understand the requirements specific to DAA - IEEE1588(PTP), non-asymmetric routing etc. make sure you dedicate the right resources to plan for that
4. **Gradual migration -** Do not underestimate the importance of starting out slowly – it is important to have enough time to capture both process glitches and technical issues and to implement the required improvements. The rollout will be unlike anything your HFC techs have tried before. Consider all tools and measurements that will be impacted by the architecture change and plan ahead. It is recommended to start field deployment with one node, and gradually increase scale for full deployment.
5. **Plant Data Quality** – Poor HFC network documentation will seriously slow down the deployment rate and results in miscommunications to customers about planned outages that may get delayed due to operational reasons. It is worth considering a site survey, in cases where there is doubt.

6. **Importance of Automation** – the significant change in the network is an opportunity to automate more processes, making it easier for the deployment team and longer term also easier for the maintenance and support teams. Specifically, automating the RPDs management is beneficial, to allow for unified interface to the devices, bulk configuration and management, inventory tracking, and debuggability of the units in the field.
7. **Partnership –** Along the entire project, the Stofa and equipment vendor's teams have kept very open communication line, and full transparency on the status of their development and readiness for the project. The close communication enabled us to quickly react or hurdles in the plan, and form work arounds together in a way that will not delay the project and push it forward.
   We recommend weekly meetings between the different integration teams, and additional ad-hoc meetings (quickly scheduled) to discuss specific issues and challenges.

In conclusion, the authors consider the Remote PHY deployment and network upgrade project to be highly successful. It provided the benefits Stofa was looking to get from transitioning to the new technology, and guarantees the Stofa network can grow and expand in the future, providing excellent service to all its subscribers.

Abbreviations

ADC	Analog to Digital Converter
CCAP	Converged Cable Access Platform
CIN	Converged Interconnect Network
CM	Cable Modem
CMTS	Cable Modem Termination System
D3.0	Data Over Cable Service Interface Specification version 3.0
D3.1	Data Over Cable Service Interface Specification version 3.1
DAA	Decentralized Access Architectures
DAC	Digital to Analog Converter
DHCP	Dynamic Host Configuration Protocol
DOCSIS	Data Over Cable Service Interface Specification
DS	Downstream
DWDM	Dense wavelength division multiplexing
FEC	Forward Error Correction
FFT	Fast Fourier Transform
Gbps	Gigabits Per Second
GHz	Gigahertz
GM	Grand Master
HFC	Hybrid Fiber Coax
HSD	High Speed Data
MAC	Media Access Control interface
MACPHY	DAA instantiation that places both MAC & PHY in the Node
MPEG	Moving Picture Experts Group
MIB	Management Information Base
MPLS	Multiprotocol Label Switching
MSO	Multiple System Operator
OFDM	Orthogonal Frequency Division Multiplexing
NFV	Network Function Virtualization
PHY	Physical interface

PNM	Proactive Network Maintenance
PTP	Precision Time Protocol
QAM	Quadrature Amplitude Modulation
R-MACPHY	Remote MAC-PHY
RPD	Remote PHY Device
R-PHY	Remote PHY
SC-QAM	Single Carrier Quadrature Amplitude Modulation
SDN	Software Defined Network
SG	Service Group
SNR	Signal to Noise Ratio
TACACS	Terminal Access Controller Access-Control System
VLAN	Virtual Local Area Network
vCore	Virtual Core
VoD	Video on Demand

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