Software-defined wired-wireless access network convergence: the SODALES approach

Jordi Ferrer Riera, Carles Bock, Eduard Escalona
Fundació i2CAT
Barcelona, Spain
{jordi.ferrer,carlos.bock,eduard.escalona}@i2cat.net

Volker Jungnickel, Kai Habel
Fraunhofer Heinrich Hertz Institute
Berlin, Germany
{volker.jungnickel,kai.habel}@hhi.fraunhofer.de

Michael C. Parker, Stuart Walker, Terry Quinlan
University of Essex
Colchester, United Kingdom
{mcpark,stuwal,quinlan}@essex.ac.uk

Victor Marques
Portugal Telecom Inovação
Aveiro, Portugal
victor-m-marques@ptinovacao.pt

David Levi
Ethernity Networks
Israel
vidi.levi@ethernitynet.com

Abstract—It is envisaged that end-user access bandwidth requirements will notably increase in the coming years; at the same time, the number of connected mobile devices will also exponentially grow as the fully-digital connected homes (Internet of Things) becomes an everyday reality. This article presents an active remote node (ARN) at an intermediate location between the central office and end-user premises, as a flexible and future-proofed infrastructure topology approach for solving the associated bandwidth and wired-wireless convergence issues. The ARN represents the key architectural design innovation of the SODALES (SOftware-Defined Access using Low-Energy Subsystems) network. The rise of mobile communications, and the trend for seamless convergence between fixed and wireless networks is tending to make the purely passive approaches (e.g. as exemplified by passive optical networking (PON) access architectures) too restrictive, considering the modularity and flexibility offered by an active remote node. We present a performance analysis of the ARN node, to support the cost-effectiveness of the proposed SODALES solution and to demonstrate the potential benefits in terms network performance, operational efficiency, and flexible functionality. Looking forward, future ARN capabilities can also be expected to include hierarchical caching, customer premises equipment (CPE) virtualization, and nearer to the end-user location of software-defined platforms supporting ubiquitous cloud services.

Keywords—access network convergence, active remote node, performance analysis

I. INTRODUCTION AND RELATED WORK

End-user access bandwidths requirements are constantly increasing. It is expected that access bandwidths of 1 Gb/s will be commonplace in the next two or three years, while 10 Gb/s will be exploited by domestic applications within the next ten years [1]. With the rise of new content-rich services (e.g. HD on-demand video, new television formats such as Super HD 4k or Ultra HD 8k) it is expected that bandwidth requirements will continue to steadily increase [2]. The expected service bandwidth increase, jointly with the appearance in the arena of business and mobile backhaul applications, is likely to create a bottleneck in today’s gigabit-class passive optical network (PON) deployments [3]. Such PON deployments between the central office (CO) and end-user have been the favored solution up to the present. In addition to the traditional services delivered both to wired and wireless end-user devices, the authors in [3] also mention another set of trends driving up bandwidth demand provision, such as: (i) the increasing number of different devices connected to the Internet (considering a fully-digital home, and the Internet of Things); (ii) the accessibility and availability of a huge range of Cloud services, for both business and residential users; (iii) the rise of online content distribution; and (iv) the coexistence of residential and business applications on a common access platform, which may drive the requirement for bandwidth-symmetric deployments. There is thus a techno-economic challenge to be addressed, in order to achieve such high-bandwidth access segments.

A great deal of industry discussion has been focused on what the technology beyond legacy GPON and XG-PON systems [4,5,6] should be, considering the service bandwidth requirements. Several options under consideration are 10G EPON [7] or NG-PON [8], including both NG-PON1 and NG-PON2 phases. However, it is becoming obvious that what network operators require, in order to serve the new emerging demands, is a more scalable, flexible, and future-proof technology solution. From one perspective, the NG-PON2 system is targeting the fulfillment of this demand trend, as well
as offering a cost-efficient PON upgrade path and a solution that fully exploits both the low transmission loss and the capacity of optical fibers. However, the critical technical and functional requirement for wired-wireless convergence in access networking is now becoming of essential importance.

Network convergence offers the prospect of optimizing the total cost of ownership for the different network operators [3]. This reduction may be achieved by means of eliminating the distinct network technology solutions in the access and aggregation domains. Thus, fixed- and mobile-backhauling must be considered in such future deployments. Converged wired-wireless environments represent a key-enabler scenario for the upcoming operators, since mobile subscribers are expected to end up representing the major part of their future business plans (considering the rise of connected mobile devices). In fact, concepts for fifth generation (5G) mobile networks are nowadays under intense discussion by both industry and academia, such that 5G is now one of the key topics within the research community. It is currently assumed that by around the year 2020, a new generation of mobile networks will have been deployed and be fully operative. Recent research has identified major challenges, such as the aforementioned massive growth in the number of connected devices, and a wider and more diverse set of requirements, starting from low data rates for control messages with a moderate latency, to multi-gigabits per second for low-latency interactive multimedia [9]. Besides these new radio concepts envisaged as part of the major challenges associated in 5G research, it is clear that the high-capacity, flexibility, and programmability requirements of 5G will have significant impact on the network infrastructure underpinning the radio part. It is commonly assumed that both the mobile and the fixed access networks will therefore need to be optimized jointly to meet all these high demands [10]. Therefore, full technical and functional convergence of fixed optical with wireless communications is one of the key requirements to be addressed for future-proofed access networks.

It is from this perspective that this article presents the Software-Defined Access using Low-Energy Subsystems (SODALES) approach for a future-proofed, converged access network architecture. The approach is based on the introduction of an Active Remote Node (ARN), taking advantage of the powering requirements of the existing base stations (BSs) for radio access within such wired-wireless converged infrastructures. The introduction of the ARN represents the key structural innovation of the SODALES network, with the focus on wired and wireless communications convergence. As part of creating a new access architecture paradigm is the additional realization that the presence of such active nodes between end-users and the central office (CO) is also likely to become an ever-more essential feature of next-generation access topologies, as intelligence and advanced network functionalities are devolved ever closer to the end-users. In the SODALES network only very basic functionalities such as statistical multiplexing at the Ethernet switches, basic bandwidth service differentiation between residential and business users, and a common backhaul infrastructure for a RBS is considered. However, looking to the future, we can expect ever greater network functional virtualization (NFV) to take place at the ARN, with local caching as part of a hierarchical content delivery network (CDN), more sophisticated service differentiation (QoS/E) for a more segmented end-user base, and additional software-defined operation of the network to maximize exploitation (e.g. for energy efficiency and operational expenditure (OpEx) purposes) of available network resources. Thus we see the SODALES ARN as the first tentative example of intelligent functionality located at an active, street level, converged network node, positioned intermediately between (fixed and mobile) end-users and the central office (CO).

The rest of the paper is structured as follows: Section 2 contains a more detailed description of the SODALES architecture, focusing on the ARN, and providing some examples on the flexibility of such a functional node. Section 2 also contains technical descriptions of the different advantages of introducing an active node in comparison with full-passive approaches. Section 3 presents the performance analysis of the ARN, via network simulations of the ARN, considering its basic configuration. Finally, section 4 concludes and presents some future work directions with respect to the ARN.

II. SODALES ARCHITECTURE; THE ACTIVE REMOTE NODE

From a physical architecture point of view, the presence of an active remote node (ARN) [11,12] at an intermediate location between the central office (CO) and end-users is the key structural innovation of the SODALES network. The ARN is relatively close (up to 300 meters) to end-users. Locating an ARN intermediate to CO and end-users goes against the (up-to-now) conventional PON philosophy of removing all active (electronic) equipment from the street level, so that there is a purely passive optical link between CO and end-user. Perceived benefits of the PON approach have been reduced energy consumption, and reduced outside maintenance costs. However, the rise of mobile communications, and the trend for seamless convergence between fixed and wireless networks is tending to make the purely PON approach too restrictive. Indeed, an ultra-broadband 5G wireless network, e.g. evolving from long-term evolution (LTE) technology, requires ever-smaller cell sizes (from micro to pico and finally to femto cell sizes), with base stations (BSs) and remote antenna units (RAUs) in relatively near vicinities to the end-users. Such BSs and RAUs need to be powered, e.g. either by a suitable line from the national electricity grid, or preferably, via local renewable (e.g. solar, wind) sources.

There have been previous examples of the use of active intermediate nodes, e.g. as seen in the Ethernet active star and Home Run architectures associated with an active optical network (AON). However, these examples have been designed with very limited functionality in a purely fixed next-generation optical access network. Likewise, the radio access node (RAN) associated with mobile networks also captures some of the functionalities incorporated within the SODALES ARN, but only with mobile access networking in mind.

Convergence of fixed optical with wireless (mobile) communications is a key functionality being investigated within the SODALES project. As part of creating a new access architecture paradigm is the additional realization that the
presence of active nodes between end-users and the central office is also likely to become an ever-more essential feature of next-generation access topologies. Of course, this goes against the PON philosophy of only passive infrastructure between end-user and CO; but since mobile communications require powered base stations at the intermediate street level, the logic of the need for active remote nodes is becoming inescapable. Indeed, by dimensioning the ARN appropriately, power/energy saving techniques can also be employed to minimize the carbon footprint. For example, limited statistical multiplexing can be employed so as to exploit the available network resources as optimally as possible.

The inevitable presence of such powered, active sites, and the desire for seamless convergence between fixed and mobile communications, allows us to take advantage of these active nodes to create the SODALES architecture with its ARN close to end-users. Such an innovative architectural approach has additional critical advantages. In particular, these advantages relate to the new opportunities for open access capabilities at the L1 layer through to the L3 layer. This provides tremendous flexibility to network providers (NPs), passive infrastructure providers (PIPs), and service providers (SPs) to have their business cases open to competitors, as increasingly required by European competition legislation. On the one hand, for incumbent operators this may present a short-term threat; however, longer term, such flexibility in open access provision is expected to also stimulate new SP and NP business models, with greater efficiencies, greater consumer choice, and greater technical innovation, such that overall, the digital citizens of the future will gain greatly in the associated flexibility, scope of technical advances, and in their individual ability to fully exploit the opportunities anticipated to emerge from the e-society envisaged for tomorrow.

The existence of the ARN also provides a technical advantage with respect to the Quality of Service (QoS) in mobile communications. In particular, by extending network intelligence closer to the end-user (i.e. out of the CO and into the ARN) the relevant bandwidth allocations, and medium access control (MAC) protocols relating to wireless access can be handled much closer to the end-user, so reducing inherent latencies caused by distance to the CO (particular where node consolidation occurs with potentially >100km long-reach PONs) as well as swifter contention resolution at the ARN. This allows for a faster, more immediate, and higher quality ultra-broadband access experience for the end-user. This is also achieved by exploiting the relevant access network resources between CO-ARN, as well as ARN-end-user, in a more efficient manner. On the one hand, the ARN enables greater energy efficiencies (as measured in joules per bit, J/b) to be achieved; but also allows the inherent capacity of the access network to be exploited in a more efficient fashion; i.e. from a capital expenditure (CAPEX) point of view, less over-provisioning is required, so leading to a leaner, more efficient deployment of network (and financial) resource. From these perspectives, the SODALES architecture offers a technically exciting and innovative perspective for future converged next-generation access networking.

Our basic SODALES architecture for an appropriately designed ARN architecture is shown in Fig. 1. In this case, the basic architecture has been designed to offer 1-Gb/s statistically-multiplexed bandwidth to 96 residential homes, in addition to providing dedicated 10-Gb/s bandwidth pipes to each of three SME companies, and finally an additional 10-Gb/s bandwidth pipe to a cellular remote base station (RBS) site, e.g. for 3G, LTE wireless connectivity etc. In this case, we have designed the ARN to consist of a 120G=3×40G Ethernet switch chassis, where the first 40G rack has 4 output ports of 10G capacity each, connected respectively to the RBS and 3 SMEs. In this case, there is no contention or statistical multiplexing. The other two 40G racks each have 48 output ports, each offering a maximum 1-Gb/s bandwidth pipe. This allows the 96 residential homes to be offered a final-drop symmetrical upstream and downstream bandwidth of 1 Gb/s, with a statistical multiplexing (over-subscription) ratio of only 1.2 (i.e. 20% over-subscription). The statistical multiplexing ratio at the upstream port of the chassis is much higher at ×6 (i.e. 500%) and represents a significantly useful degree of optimal exploitation of network resource. As can be seen from Fig. 1 a total of 20 Gb/s (equal to 2×λ @10 Gb/s/λ) light paths are used between the ARN and the CO. These can be considered as the allocated wavelengths in a XG-WDM-PON backhaul system, such that rather than terminating the ONT at the customer premises as would be conventionally expected, the ONT is actually located at the ARN, and terminates with the 120G Ethernet switch. Apart from this, the XG-PON functions are conventional, with an intermediate arrayed-waveguide grating (AWG) wavelength-routing light paths to other ARNs, or even allowing dedicated wavelengths to be directly routed to a 10G ONT located at a RBS or SME business premises. The XG-PON technology, which is fully passive and uncontented between CO and ONT, is therefore fully taken advantage of; but with the ONT located at the ARN, this enables the flexible final-drop technologies: either wired (fibre-optical, FTTH) or wireless (radio/mm-wave/optical) to the residential home, and likewise convergence with mobile communications. We note that at this stage, the functionality of the ARN is kept to a minimum. Handover functions (e.g. vertical, between macro/femto cells, for example; or horizontal, between femto/femto cells etc.) are not performed at the ARN; neither is a cognitive nor any co-operative function performed locally here. As a means to be fully backwardly compatible
with legacy mobile technology, and maintaining a simple (cost inexpensive) ARN solution, any such network intelligence functionality is assumed to be performed at the CO. Looking to the future, once the ARN technological concept becomes more familiar and common-place, we would expect that further advanced and intelligent photonic network functionalities, e.g. energy-efficient caching [13], and/or local routing of local traffic will also be migrated closer to the end-user at the actively-powered ARN.

The basic SODALES ARN architecture as indicated in Fig. 1 above has been configured for maximum flexibility with respect to service provision to residential and light industry (i.e. SME) end-users, and also to provide front/back-haul bandwidth to a RBS. However, it could be the case that the ARN is located in a purely residential area, without any SME or industry requirements, e.g. in particular, this could be the case for a block of flats, or other high-density residential location. In which case, the ARN data bandwidth totaling 30 Gb/s that was previously allocated towards SME use can now be reallocated to residential users. In this case, a total of 168 residential homes can now each be served with symmetric 1-Gb/s data bandwidth, and a RBS with 10 Gb/s.

![Fig. 2. Alternative SODALES ARN architecture, serving 168 homes each with 1Gb/s, and one Remote Base Station with 10Gb/s bandwidth pipes.](image)

The number of additional residential homes served is a function of the available port-counts of the respective Ethernet switches. In particular, for the 40G switches, there is a maximum 48 output ports available; whereas for the 10G switches this reduces to 24 output ports. In which case, the three 10G Ethernet switches no longer dedicated to SME customers can now be reallocated to a total of 3 × 24 = 72 residential homes, so that the total number of homes served by the ARN comes to 168 domestic units. The presence of a RBS is still highly desirable, e.g. located on the roof of the block of flats etc., so as to provide converged and seamless mobile broadband access. Hence the RBS functionality is maintained in this alternative ARN architecture as indicated.

Finally, we note that the presence of an ARN intermediate the CO and end-users can provide important infrastructure capability for network functions virtualization (NFV), e.g. for customer equipment, as well as for the ARN equipment resource optimization. In addition, the ARN also enables a software-defined virtual platform [15], e.g. to support ubiquitous ultra-high-speed wireless/wired access, for providing connectivity and Cloud Services not just to end-customers, but also to sensors and other actuators for potential use in Smart Cities, and machine-to-machine communications required for the Internet of Things.

III. ARN SIMULATIONS

Network simulations have been carried out in order to demonstrate the superior performance of the network when introducing the ARN. The SODALES project is at present prototyping the ARN to validate its performance in a real environment and prior to this, simulations have confirmed its performance. Figure 3 depicts the ARN basic data plane utilized. The internal non-blocking architecture of the ARN offers also complete resilience. With this configuration, the limiting factor of the device will be the input / output ports.

![Fig. 3. ARN Basic data plane](image)

The basic configuration of the ARN offers 20-Gb/s uplink capacity, by means of 2 × 10 Gigabit Ethernet ports in a 1+1 redundant configuration. The residential customers are connected by means of 96 × Gigabit Ethernet ports while 4 × 10 GE ports allow the connection of SMEs and RBS. Thus, the potential customer capacity is up to 136 Gb/s. This means that the oversubscription between the uplink and the customer ports is lower than 1:7. Simulated performance of the SODALES ARN was modelled by means of discrete-analysis tools. Real traffic patterns were used as the starting point for the network load, such that traffic profiles of existing FTTH networks were used as a baseline for the simulations. These consisted of triple play services combining voice (VoIP), video (IPTV) and data. Figure 4 contains the basic simulation model utilized for the ARN, considering the aforementioned data plane.

![Fig. 4. ARN simulation model](image)
Data services ranged from 100-Mb/s to 1-Gb/s symmetric. Simulations were performed for different traffic loads, until the performance of both systems saturated.

![Fig. 5. Network traffic of a real FTTH network offering 100 Mb/s to 500 subscribers. Note that downstream traffic tends to be limited by the server side, while upstream reaches maximum customer capacity.](image)

End-users were differentiated depending on their traffic profile, between residential subscribers, SMEs and traffic coming from the RBS. Each of the traffic patterns had different loads depending on the time of the day, and were also taken from real data. GPON systems provide a data stream of 2.5 Gb/s in the downstream direction, and a 1.25-Gb/s upstream channel. These are shared typically between 64 users. The theoretical capacity of the SODALES architecture is 8 times more than GPON, and unsurprisingly, the total throughput of both systems was limited by the uplink interface in the SODALES architecture and the downstream / upstream maximum data rate in GPON. GPON systems offer optimized bandwidth allocation protocols that allow between 96% and 98% of the available channel capacity.

![Fig. 6. Traffic baseline for the different users](image)

In any case, the interesting results come from using real traffic patterns within both architectures, and comparing their performance. The fact of offering higher data rate input / output ports allows the system to provide much higher scalability. Statistical multiplexing factors increase with network capacity, and therefore, the higher the data rate to the end-user is, the higher the achieved multiplexing factor. When data rates exceed 100 Mb/s, the channel utilization of typical end-users dramatically decreases, as the devices (laptops, smartphones, or even tablets) connected to the network do not generate enough traffic to saturate the channel. Also, video streams offer burstier traffic shapes, which have a better behaviour in a multiplexing environment.

As more capacity is available, transmission times are reduced, and this also reduces the time the channel is busy. Lower times of service improve network latency and system capacity. In GPON systems, we have simulated end-user services up to 300 Mb/s with no loss of quality of experience (QoE), while for the SODALES network a solid 1-Gb/s service for residential and 10GbE for corporate users can be offered without having the perception of having a shared media with 99.99% probability. The network uplink barely limits the performance. Figure 7 contains the comparison between GPON and SODALES, while Figure 8 depicts the traffic load used of a real FTTH that has been used for the simulations.

![Fig. 7. Network simulations and comparison of a GPON network and the SODALES architecture (GPON limited to 2.5 Gb/s downstream capacity and SODALES to the 2×10GbE aggregation interfaces)](image)

![Fig. 8. Traffic load of a real FTTH deployment used for the simulations](image)

This envisages two interesting conclusions: the first one is that GPON can not offer Gigabit data rates using 1:64 splitting factors (to offer these data rates, the splitting factor should be 1:16 or below); and the second is that the SODALES network is not limited by the uplink, and therefore more GbE ports can be added to the ARN or some of them can be upgraded to offer more 10GbE services. The point is therefore reached where the
available network capacity becomes a commodity and the channel remains inactive most of the time. This starts to happen with data rates higher than 300 Mb/s. The fact that currently there is no application that uses the available capacity of a GbE access connection could imply that at present, the killer app of Gigabit Networks is the speed itself and the instantaneous response of the network (reduced latency).

IV. CONCLUSION AND FUTURE WORK

We have presented the SODALES approach for a converged access network. The approach is based on the introduction of an Active Remote Node (ARN), taking advantage of the power required to feed the base station for radio access within wired-wireless converged infrastructures. The rise of mobile communications, and the trend for seamless convergence between fixed and wireless networks is tending to make the purely PON approach too restrictive. Indeed, an ultrabroadband 5G wireless network, e.g. evolving from long-term evolution (LTE) technology, requires ever-smaller cell sizes (from micro- to pico- and finally to femto-cell sizes), with base stations (BSs) and remote antenna units (RAUs) in relatively near vicinities to the end-users. Such BSs and RAUs need to be powered, e.g. either by a suitable line from the national electricity grid, or preferably, via local renewable (e.g. solar, wind) sources. Thus, taking benefit of the power brought to the BSs and RAUs, we introduce the ARN with further flexibility and capabilities in order to address the emerging requirements. We have presented numerous technical advantages of introducing such node in section 2.

We have presented preliminary ARN performance simulations in order to demonstrate how the ARN provides higher network performance as compared with current deployed PON solutions (i.e. GPON). The techno-economics analysis of installing and deploying the active node in terms of CapEx is out of scope of this article, although some work demonstrating a lower cost per Mb/s was presented in [14]. The results presented show how the SODALES network, including the ARN, is not limited by the uplink, and therefore more GbE ports can be added to the ARN or some of them can be upgraded to offer more 10GbE services and therefore increase the end-user bandwidth or backhauling capacity, depending on the configuration selected.

Considering the obtained results and the trends towards ultra-broadband 5G networks to be deployed in 2020, the door to future research work on the active remote node remains clearly open. In this sense, there are two main directions on the future work. On the one hand, there is the issue of ARN interconnection (for resilience, and more localized traffic management), which has not yet been rigorously considered. Thus, one approach may be to consider the use of OFDM-PON to interconnect the different remote nodes in a metro-access convergent scenario. On the other hand, and again taking into consideration the virtue of being powered, the ARN may exploit the substantial operational and economic advantages in aggregating traffic at intermediate points with standard Ethernet switching technology, together with offering Cloud Services, Content Caching within content delivery networks, and virtual CPE (V-CPE) features in order to reduce traffic aggregation to the atniral office.

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