Centralised versus Distributed Radio Access Networks: Wireless integration into Long Reach Passive Optical Networks

Christian Raack
atesio GmbH
Berlin, Germany
raack@atesio.de

Julio Montalvo Garcia
Telefónica I+D
Madrid, Spain
julio.montalvogarcia@telefonica.com

Roland Wessäly
atesio GmbH
Berlin, Germany
wessaely@atesio.de

***Abstract*—In this paper we evaluate the cost of wireless integration into an architecture based on long reach passive optical networks (LR-PON). We will prove that including backhaul or fronthaul signals from antenna sites into existing LR-PON structures deployed for wired customers requires only marginal additional resources. We will also show that scenarios with remote radio heads and centralised base band units outperform distributed radio access networks mainly because of operational cost savings.**

I. Long Reach PONs and Metro Core Nodes

The FP7 project DISCUS is investigating an optimised end-to-end optical network architecture considering Long-Reach (LR) passive optical networks (PONs) and a flat optical core [1], [2]. The LR-PONs technology approach in DISCUS consists of a hybrid Time and Wavelength Division Multiplexing (WDM) of symmetrical 10 Gbps optical channels to communicate the remote devices in a PON (ONUs) with the central office equipment (OLTs). While the most advanced PON standard is currently designed to offer up to 8 of these 10 Gbps symmetrical channels [3], DISCUS LR-PONs are designed to support up to 40 of these channels [4]. Moreover, DISCUS is investigating and developing the technologies required in order to support simultaneously a 100km or even 125km reach and 512 split ratio in LR-PONs. With these values, DISCUS allows a very high consolidation of PONs into a minimum number of Points of Presence, where the access, the metro/aggregation and photonic transmission layers are comprised in the same network node, namely an MC (metro-core) node.

In this respect, DISCUS revisits the classical divide between access, metro, and core networks for a new future proof end-to-end network architecture for next-generation communication networks. Central to the DISCUS LR-PON is a dual-homing architecture, see Fig. 1. The optical signal is supposed to pass a three-stage splitting hierarchy from the MC node to the customer. The first stage splitter already located at a local exchange site, is used to provide a redundant connection to a second MC node. In consequence, every LR-PON by-passes an LE site and is connected with two different MC nodes. Clearly, due to the quadratic scaling of connections in the full mesh of the optical island a small number of MC-nodes is indispensable for this architecture to be cost-effective and scalable.

In this paper, we study the impact of wireless integration into an architecture based on LR-PONs. We will prove that including backhauling or fronthauling signals stemming from antenna sites into the PON structures originally deployed for wired customers requires only marginal additional resources. We will also show that scenarios with remote radio heads and centralised base band units outperform distributed radio access networks because of operational cost savings.

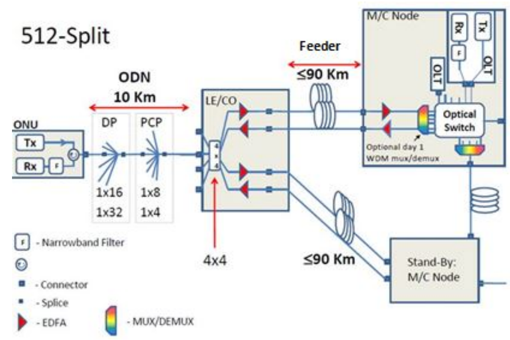


Fig. 1. The DISCUS LR-PON architecture: A multiple splitting hierarchy between customer and LE and dual-homing between LE and MC. The local exchange houses the first stage 4x4 split and also acts as an amplifier node. The MC node acts as the access optical line termination as well as a core router with L1/2/3 switching and routing functionality.

II. Centralised versus Distributed Radio Access Networks

The centralisation of the base-band processing of radio networks appeared as an option to traditional radio access networks (RAN) because it may reduce capital and operational cost, as well as facilitate the implementation of advanced radio features such as Coordinated Multi-Point (CoMP) transmission and reception. In centralised radio access networks (CRAN), the antenna sites are simplified with Remote Radio Heads (RRH) with no base-band processing, in opposite to the distributed RAN (DRAN). This allows CRAN to achieve a more easy installation of small RRH, also allowing to reduce the overall base-band processing resources due to the statistical gain of centralisation. Nevertheless, it is well known that the demand of transport resources to deliver the signals from the RRH to the Base-Band Unit (BBU), where the fronthauling signals are processed, increase drastically. This may reduce the opportunities for CRAN to be a cost-effective scalable solution when considering 4G and 5G scenarios with ultrahigh speed capacity (1-10 Gbps) offered to the mobile user equipment in the radio layer. Due to the high split ratio and scalable capacity of DISCUS LR-PONs, the support of DRAN services by the fixed fibre network seems a feasible and cost-effective approach for fixed-wireless convergence. Nevertheless, DISCUS LR-PONs open also a new possibility for a cost-effective fixed-wireless convergence with CRAN, because a high number of high speed common public radio interface (CPRI) signals can be transported into the same LR-PON using dedicated wavelengths in a Point to Point fashion, instead of requiring dedicated fibre links. We refer to Fig. 2 for integrating the DRAN backhaul and CRAN fronthaul into the LR-PON DISCUS architecture.

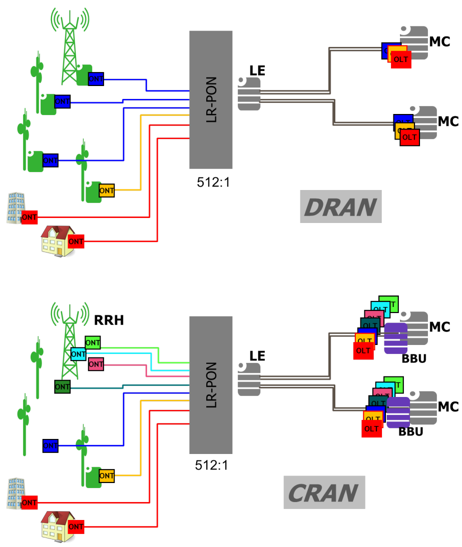


Fig. 2. The DISCUS LR-PON architecture with integrated antennas. a) DRAN integration, 32 sites may share the same wavelength. b) CRAN integration, each sector requires its own wavelength in the WDM PON.

III. REFERENCE NETWORKS AND CORE NODE DISTRIBUTIONS

In order to provide realistic studies of wireless integration into LR-PONs including fibre routing and concrete positioning of antenna sites and local exchanges we use reference networks reflecting nation-wide fibre topologies. This approach allows to properly incorporate the influence of topological connectivity (for resilience issues) and technological restrictions such as maximal distances. For this study we developed reference networks for the UK, for Italy, and for Spain using data from BRITHISH TELECOM, TELECOM ITALIA, and TELEFONICA. The provided data sets for the UK and Italy included anonymized (shifted) coordinates of local exchanges (central offices) together with the number of connected customers. For Spain, we used detailed population statistics and high-level characteristics of the local exchange distribution in Spain to estimate their positions and customer assignment.

Already in [5] and [6] we showed how to combine this operator specific information with public available data, namely with data from open street maps [7], in order to come up with realistic fibre topologies. Such geo-referenced data from street networks is a reasonable choice in this case as laying fibres is typically done along streets and street networks provide

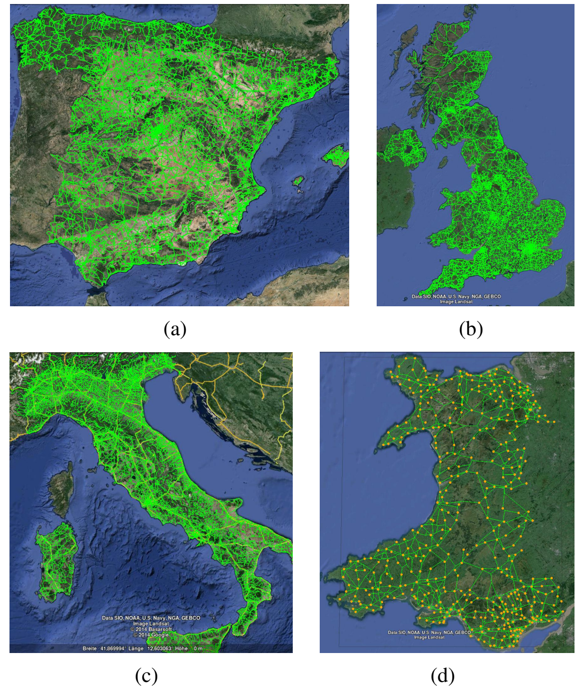


Fig. 3. (a) The Spanish network (b) The UK network, (c) The Italian network (d) Wales: A clipping from the UK network.

a correct notion of distance. They reflect dense and sparse structures, towns and rural areas, mountains, valleys, and river crossings.

We constructed fibre reference networks for each of the three countries, also see [8]. The dimension of the individual networks is given in Table I, also see Fig. 3.

TABLE I. REFERENCE NETWORKS

Instance	nodes	links	LEs	households
Spain	18,819	26,479	8,272	20.6 Mio
UK	15,609	23,025	5,578	29.4 Mio
Italy	23,689	32,700	10,620	24,9 Mio

Based on these networks, it has been investigated how many aggregation MC nodes are required within these countries to allow for consolidating all current local exchanges (LEs) within a given distance and also with different assumptions on the resiliency level and maximum MC node size, see [6], [5]. Potential MC nodes are all LEs with a certain level of connectivity. Table II reports on solutions we obtained assigning local exchanges to MC nodes, also see Fig. 4. In all these solutions each customer gets connected to two different MC nodes while the feeder fibres take two disjoint routes (dual-homing between LE and MC) in the cable network [1], see Fig. 1 and 2. We allowed a maximum customer-to-MC distance of 125 km. Table II also states the maximum number

TABLE II. MC NODE DISTRIBUTIONS.

Instance	# MCs	max MC Dist	max MC Size
Spain	110	125 km	1.0 Mio
UK	73	125 km	1.0 Mio
Italy	116	125 km	2.6 Mio

Fig. 4. MC node distribution in Italy: MC nodes with more than 1 Mio customers in red, those with less than 50 K in white.

of (primary plus secondary) customers (max MC Size) at the same MC. The Spanish (mainland) and UK solutions have been optimised to have at most 1 Mio customers at each MC. In these solutions we did not respect regional boundaries (except for Northern-Ireland). For the Italian solution we did not use a maximum customer constraint but respected regional boundaries (20 administrative regions), that is, an LE in Veneto does not connect to an MC in Lombardia, etc..

IV. Antenna site distribution

Distributing antennas to achieve full coverage within a country is clearly a non-trivial task. Locally, it depends on cellular layout, antenna parameters such as antenna height, azimuth direction, or beamwidth, as well as regional characteristics such as mountains or buildings. Globally, it is further complicated by the fact that the reach of the antennas and the corresponding cell radii typically depend on the considered geo-type. Dense urban areas contain many base stations with small reach antennas (cell radii below 500m) to serve a large amount of customers within a small area, while rural areas are served with only a few antennas and cell radii of a few kilometres.

In order to study DRAN versus CRAN deployment and cost we start from a nation-wide distribution of antenna sites implementing assumptions of population density and cell radii shown in Table III. In order to determine a nation-wide geo-type distribution we use the information about connected customers at the LE coordinates, see below.

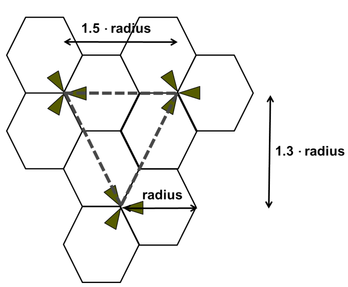


Fig. 5. Tessellation with clover leaf layout: Sector and cell structure. The site-to-site distance is 1.5 times the site radius. This radius corresponds to the diameter of the shown hexagons, which in turn corresponds to the reach of the individual sector antennas.

From the mathematical perspective, given a certain cellular layout, covering a country with cells can be seen as a tessellation of the plane. Hexagonal layouts as shown in Fig. 5 have been studied extensively, see for instance [9], [10], [11] and the references therein. Such simplified hexagonal tessellations and the resulting layout characteristics such as the positioning of antennas to each other and the number of sector can be used to study crucial aspects in cellular deployment such as interference between neighboured cells.

Based on a given geo-type, our deployment of antenna sites follows a 3-sector hexagonal clover-leaf layout, see Fig. 5 ([10]). Each *sector* antenna spans a hexagon as shown in Fig. 5 such that the *antenna site* sits on the edge of the three hexagons. In the following, if we speak of a (three-sector) *macro cell*, we refer to these three hexagons. The *radius* of a macro-cell is given by the reach of the sector antennas, which results in a site-to-site distance of 1.5 times the radius. In the resulting grid of antenna sites two rows have a distance of $3\sqrt{3}/4 \sim 1.3$ times the macro cell radius.

Notice that we will use the terms macro cell, antenna site, and base station as synonyms throughout this paper, that is, the antenna site houses one base station and spans one macro cell (of one technology).

TABLE III. Cell model based on population density

Geo-Type	Homes/km^2	cell radius (m)
Dense Urban	$\geq$ 4000	250
Urban	2000 - 4000	500
Sub-Urban	500 - 2000	1000
Rural	10 - 500	2000
Sparse Rural	0 - 10	10000

For deciding about the population density we consider five geo-types: *Sparse Rural*, *Rural*, *Sub-Urban*, *Urban*, and *Dense Urban*, which are defined by the number of households per square kilometre. Depending on the local geo-type we deploy antenna sites with the radius given by Table III. This automatically leads to a very dense distribution of sites in (dense) urban areas and a very sparse distribution of sites in (sparse) rural regions.

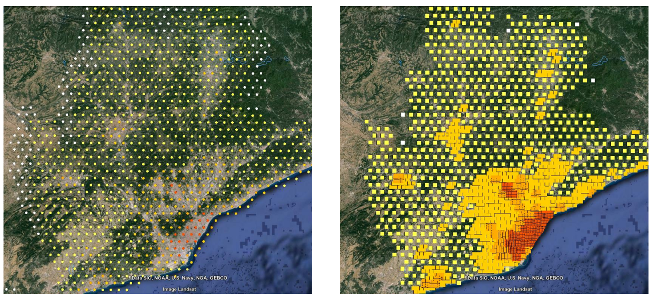
To deploy antenna sites within a given geo-type region we use a heuristic that starts from a regular grid G as in Fig. 6(a) assuming a regular Rural tessellation with macro cells of radius 2 km. The heuristic then adds or removes sites if necessary, that is, if the geo-type actually differs. In fact, we make use of the fact that most of the country area is actually Rural and that the geo-type radii are multiples of each other. We further use a description of the given country as a (typically non-convex and simple) polygon R (or several polygons if necessary). In this context it is important to be able to decide whether a given coordinate point is contained in R or not, which can be done very fast also for large polygons with many edges using the famous crossing number algorithm [12].

The heuristic then consists of three essential steps:

1) Compute the actual geo-type $geo(g)$ of each of the grid points $g \in G$ by counting the number of households (connected to LEs) in a box around g. Let $r(g)$ be the macro cell radius from Table III corresponding to $geo(g)$.
2) Iterate the grid points $g \in G$. If $r(g) < 2km$, that is, if $geo(g)$ is either Sub-Urban, Urban, or Dense Urban,

TABLE IV. MACRO CELL DEPLOYMENT: GEO-TYPE AREAS AND RESULTING MACRO CELL DEPLOYMENT.

Country		Total	S.Rural	Rural	S.Urban	Urban	D.Urban
Spain	Area		43.4%	53.5%	2.8%	0.2%	0.1%
	Macro cells	34,689	5.1%	61.8%	20.5%	6.8%	5.8%
Italy	Area		11.1%	84.1%	4.4%	0.3%	0.1%
	Macro cells	41,276	1.0%	71.0%	17.9%	4.9%	5.2%
UK	Area		23.4%	67.1%	7.7%	1.5%	0.3%
	Macro cells	44,309	1.2%	42.4%	24.1%	18.7%	13.7%



(a) (b)

Fig. 6. Cell deployment in the Barcelona region. The colours correspond to the geo-types; white: Sparse Rural, yellow: Rural, light-orange: Sub-Urban, orange: Urban, red: Dense Urban; (a) Initial grid G (b) Resulting antenna site deployment

then a single antenna at g does not suffice to cover the neighbourhood of g. If $A(Rural)$ is the area covered by a Rural antenna site and $A(geo(g))$ the area covered by a site of geo-type $geo(g)$, then $\lceil A(Rural)/A(geo(g)) \rceil$ gives the number of required antenna sites. We use the clover-leaf layout (Fig. 5) to distribute these sites in the considered area around g. For each new site we check whether it is contained in the countries polygon R.

3) Randomly chose one of the grid points g of type Sparse Rural. We place a Sparse Rural site at g. This yields a coverage area of $A(SparseRural)$ larger than $A(Rural)$. Remove all grid points and antenna sites in this area from G and iterate.

Notice that the tessellation with Sparse Rural antenna sites in Step 3) does not necessarily follow a regular clover-leaf structure. Further, as mentioned above, we are not given geographical coordinates of households but of local exchanges. That is, in Step 1) we can only estimate the geo-type of a grid point. Given a grid point we start with a box of 3 km width having the grid point in the centre to estimate the geo-type. We then iteratively increase the radius to 10 km. We only change the geo-type in this iteration if the change is towards a more urban geo-type (higher population density).

Fig. 6(b) shows an exemplary deployment using our heuristic in the Barcelona area. Table IV provides detailed numbers of the cell deployment for the countries Spain, Italy, and UK. It can be seen that most of the countries area is Sparse Rural and Rural. Clearly, among the eventual macro cells there are only few Sparse Rural because of the large radius. In contrast, the few Dense Urban regions create a significant number of cells because of the small cell radius. The deployment depends strongly on the considered country. While Spain is relatively Rural there is a significant portion of (Dense) Urban cells in the UK. Note that the number of sites in Table IV is larger but in the same order of magnitude as those deployed today in the considered countries.

V. PARAMETERS

In order to perform a comparison between DRAN and CRAN using LR-PONs, we focus on a future possible RAN scenario. This includes the offer of a peak access of 1 Gbps at the radio layer per cell. For DRAN, a statistical aggregation efficiency of 3.2 per antenna site is assumed, thus up to 32 antenna sites could share the same 10 Gbps channel in a single LR-PON to perform the backhaul of the IP traffic. In order to achieve the same throughput in the CRAN approach, the required fronthauling capacity for each sector is around 25 Gbps, thus we assume a 1/3 compression ratio [13] in order to transport the digital RoF (Radio over Fibre) signal from the RRH to the BBU using a 10 Gbps Point to Point LR-PON channel. Due to latency restrictions required to guarantee the throughput performance, for CRAN we also consider a limited maximum distance from the RRH to the BBU of 40km [14].

Translating these assumptions to side-constraints for optimising the LR-PONs we obtain the following

- There is no constraint on the maximum fibre distance between the antenna site and the metro core node for DRAN. That is, we may use the full LR-PON distance of at most 125-km.
- There is a hard distance constraint for CRAN deployment. The base band unit can only be centralised at the MC node if the (primary) fibre route from the antenna site to the MC node has at most 40 km.
- At most 32 DRAN cells share the same colour in the same PON, each sites requires one port. In contrast CRAN cells require 3 colours, one per sector.
- The WDM LR-PON supports up to 40 colours.

VI. WIRELESS INTEGRATION

We will study the integration of wireless backhaul and fronthaul signals starting from an existing deployment for wired customers (households). We will of course ignore PON specific detailed aspects such as man-holes, splicing or floating of cables, micro-ducts, etc., but concentrate on the main structure of the LR-PONs in terms of cabling, splitting, and port fill. We will also not consider all cost factors that are crucial when considering PON deployments but concentrate on those resources that are effected or differ in a DRAN versus CRAN deployment. For instance, we will see that we can safely ignore duct resources as the required fibre/cable resources do not increase significantly enough neither in a DRAN nor in the CRAN approach compared to the LR-PON deployment based on wired clients only. In the following, if we speak of *customers*, we refer to any wired client of the PON, so residential households or business customers. This is opposed to the wireless clients, which are the antenna sites.

No coordinates for residential households are available for the reference countries. That is, we can only estimate the required LR-PON resources in the optical distribution network (ODN), which refers the PON segment below the LE towards the clients. However, we are able to determine the (lower

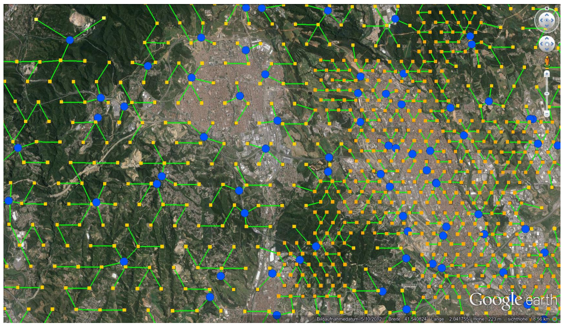


Fig. 7. Trees among site location in order to evaluate cell-to-LE distances. Orange dots indicate site locations (Sub-Urban and Urban). Blue dots are the local exchanges.

bound) of required PONs below a given local exchange as both the number of customers at the LE as well as the number of antenna sites is given to us. We simply assume that each macro site is assigned to the closest LE. Similarly, the total number of required ONUs and OLTs does not depend so much on distances but on total numbers of households, antenna sites, and resulting PONs.

In contrast, cabling and splitting in the ODN depends on the location of all PON clients. Nevertheless, with the coordinates of antenna sites from the cellular deployment and with some additional assumptions on average distances for households as well as assumptions on the splitter hierarchy we will at least estimate fibre distances in the ODN in order to approximate required fibre resources. For the feeder section (between LE and MC) we have relatively accurate numbers as the cabling here only depends on the number of PONs bypassing the LE and the disjoint fibre routes towards the MC nodes, which we are given from the MC node distributions presented in Section III.

Summarising, even without exact coordinates for buildings we will have reasonable numbers for PON deployments including wired customers and including DRAN, CRAN cells. The numbers for fibre kilometres and splitter resources in the ODN can be seen as rough estimations while the numbers for PONs, OLTs, ONUs, and required cable resources in the feeder section are very good indicators.

Given some distribution of MC nodes from Table II, a distribution of macro sites from Table IV, and an assignment of local exchanges to a primary and secondary MC node, we can compute the distance between an antenna site and an MC node. The LE-to-MC fibre distance is taken from the fibre route to the primary MC. For the antenna-to-LE distances we build a spanning tree between all sites corresponding to the same LE (the closest as mentioned above), see Fig. 7. The distance of an antenna to the LE is defined by the unique path in that tree. Notice that we design the weights in the minimum spanning tree computation so as to (heuristically) minimise distances towards the LE.

As mentioned above, a CRAN solution is feasible only if the antenna-to-MC distance is at most 40 km. However, even with this 40 km distance restriction, LR-PONs with a maximum reach of 125 km offer a good solution to cover the most populated areas with CRAN. Table V shows that for all solutions we can reach more than 50% of the customers with a centralised radio access architecture. The share of CRAN cells increases with the population density. For (dense) urban areas we achieve a coverage of typically more than 70% with values up to over 90% depending on the MC node density. Notice that the average MC node density is larger for Italy as we respect regional boundaries in the 116 node solution.

Notice that we deploy DRAN in areas where CRAN is not feasible due to longer distances providing a mixed DRAN/CRAN deployment. Whenever stating a CRAN solution we provide the percentage CRAN coverage in brackets.

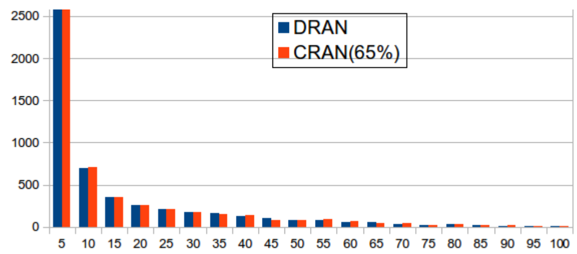
TABLE V. PERCENTAGE OF CELLS AND CUSTOMERS THAT CAN BE REACHED WITHIN 40 KM FROM THE MC FOR DIFFERENT MC-NODE DISTRIBUTIONS. THESE SITES ARE CRAN FEASIBLE.

Country	MCs	Reached Customers	Reached Sites S.Rural	Rural	S.Urban	Urban	D.Urban
UK	73	65.0%	23.0%	53.0%	68.0%	70.0%	70.0%
Spain	110	52.0%	26.0%	40.0%	60.0%	63.0%	64.0%
Italy	116	70.0%	27.0%	50.0%	75.0%	93.0%	98.0%

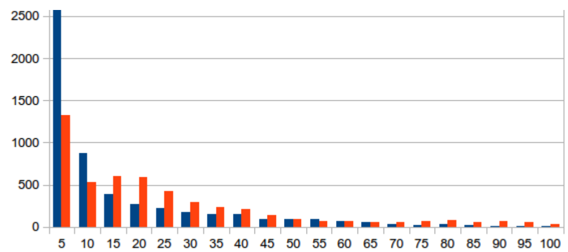
a) Filling the PONs: When filling the PONs we ignore exact positioning of both antennas and wired customers. Instead we use the fact that each PON has two capacities: at most 512 ports and at most 40 colours can be used simultaneously. To cope with topological characteristic when filling all ports of the same PON, we assume a filling factor of 80%, which means that at most 410 ports can actually be used, c. f. Fig. 8(c). There are three types of clients that use resources of the PON in a different way. Recall that each colour of the PON has a capacity of 10 Gbps, which may be shared among the 410 ports: (i) A wired customer uses one port of the PON. At most 410 such customer clients may use the same colour. (ii) A DRAN macro cell uses one port of the PON. At most 32 such DRAN cell clients may use the same colour. (iii) A CRAN macro cell has three sectors and uses three ports of the PON. Each sector needs its own colour. Our algorithm to fill the PONS works iteratively. We simply start with the customers and fill ports, opening new PONs if necessary. We then iterate first the DRAN cells and then the CRAN sectors successively filling the ports. We open new PONs and use new colours if necessary. Customers always use the same colour. DRAN cells use colours different from customers and CRAN sectors use colours different from DRAN cells and different from customers. See Fig. 8 for typical PON fill statistic resulting from our algorithm.

b) OLTs and ONUs: Computing the number of OLTs required at all MC nodes to serve the PONs is simple and follows directly from the number of used colours at the PONs. Each colour needs a serving OLT. The number of ONUs at the client side equals the total number of used PON ports.

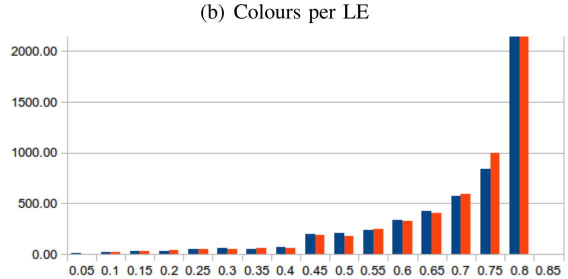
c) Approximating the number of splitters: To approximate the number of required splitters we fix the splitting hierarchy. In case of PONs for customers or DRAN cells or mixed PONs it is possible that all 410 available ports are actually used, that is, in these cases we assume a 512 split with a 1x8 splitter at the cabinet and a 1x16 splitter at the DP besides the 4x4 splitter at the LE, see Fig. 1. If k is the number of 512-PONs (customer, DRAN, or mixed PONs) then k 4x4 amplifier splitters, $4k$ 1x8 cabinet splitters and $32k$ 1x16



(a) PONs per LE



(b) Colours per LE



(c) PON fill per LE

Fig. 8. UK solution, 73 MCs. The y-axis shows the number of LEs that achieve the performance indicator on the x-axis. (a) Average number of PONs (b) Average number of colours (c) Average PON fill (1.0 = 512 ports; 0.8 = 410 ports)

DP splitters are required. In contrast, in case of pure CRAN PONs at most 40 ports can be used. We assume that the cabinet splitter is omitted in this case. This gives a $4 \cdot 16 = 64$ split. That is, if the number of CRAN PONs is k' then we have k' additional 4x4 amplifier and $4k'$ additional 1x16 DP splitters.

d) Approximating cabling: We will ignore the cost for ducts as we have not seen big differences in the cable deployment for the different macro cell scenarios (only wired customers, additional DRAN deployment, mixed DRAN/CRAN deployment), see below. That is, we do not expect any significant change in the duct infrastructure because of wireless integration if only macro cells are considered. To compute cable resources in the LR-PON we distinguish drop cables to connect clients to the PON, ODN cables for the segment between first and last splitter, and feeder cables for cabling between LE and MC. For the latter we have precise numbers for both the actual fibre routes and the number of fibres following these routes (based on the number of PONs). We use a feeder cable model with cables of different sizes having between 48 and 276 fibres, see Table VIII. For the Drop-section, the section between the client and the DP splitter, we use a single-fibre cable, see Table VIII. To approximate the required total Drop cable resources we assume Drop distances that depend on the geo-type. For all clients we assume an average distance of 50% of the macro cell radius corresponding to the same geo-type, that is, a distance between 125m (Dense Urban) and 5km (Sparse Rural), see Table III. For clients without individual geo-type we assume the same geo-type as most of the cells at the same LE. For the ODN section and wired clients we assume an average fibre distance of 100% of the corresponding geo-type. However for macro cells we can obtain a more precise value since fibre distances to the local exchange can be obtained from the spanning tree mentioned above. We follow the general assumption that the cabinet splitter is located close to the LE. Since we assume a 1x16 splitter at the DP we divide the client numbers by 16 to obtain the number of fibres in the ODN. In the ODN we assume cables with 8 fibres on average.

TABLE VI. DRAN AND CRAN DEPLOYMENT AND REQUIRED SUPPLEMENT RESOURCES COMPARED TO PURE RESIDENTIAL LR-PONS (BASE) – UK INSTANCE WITH 73 MCS, 5,578 LES, AND 44,309 ANTENNA SITES, AND 29.4 MIO WIRED CUSTOMERS.

Entity	Base	Supplement DRAN	Supplement CRAN (65%)
Backhaul Fiber km	14,078,841	0.16%	0.88%
Backhaul Cable km	102,259	0.08%	0.41%
D-side Fiber km	1,737,453	0.42%	1.26%
Drop Fiber/Cable km	13,899,625	0.21%	0.64%
PONs	74,397	0.16%	1.14%
Cabinet splitter	297,588	0.16%	0.16%
DP splitter	2,380,704	0.16%	1.14%
ONUs	29,373,914	0.15%	0.34%
OLTs	74,397	7.53%	114.80%

TABLE VII. DRAN AND CRAN DEPLOYMENT AND REQUIRED SUPPLEMENT RESOURCES COMPARED TO PURE WIRED CUSTOMER LR-PONS. WE REPORT ON THE PURE MACRO-CELL DEPLOYMENT AS WELL AS ON A DEPLOYMENT WITH ADDITIONAL 8 OR 16 MICRO CELLS PER MACRO CELL.

Country	Scenario	PONs	Feeder	ODN	Splitters	OLTs	ONUs
UK	DRAN	0.2%	0.2%	0.2%	0.2%	7.5%	0.2%
	CRAN(65%)	1.1%	0.9%	0.7%	1.0%	114.8%	0.3%
	DRAN-8	1.3%	1.3%	3.4%	1.3%	20.9%	1.3%
	CRAN-8(65%)	8.7%	6.9%	3.8%	7.9%	415.3%	1.5%
	DRAN-16	2.4%	2.4%	6.5%	2.4%	36.5%	2.5%
	CRAN-16(65%)	16.2%	12.8%	6.9%	14.7%	716.9%	2.7%
Spain	DRAN	0.2%	0.2%	0.3%	0.2%	13.5%	0.2%
	CRAN(52%)	0.5%	0.4%	0.8%	0.4%	97.1%	0.3%
	DRAN-8	1.4%	1.4%	3.4%	1.4%	25.3%	1.4%
	CRAN-8(52%)	6.0%	4.9%	3.9%	5.5%	335.2%	1.6%
	DRAN-16	2.6%	2.6%	6.5%	2.6%	42.1%	2.7%
	CRAN-16(52%)	11.7%	9.5%	7.0%	10.7%	575.9%	2.9%
Italy	DRAN	0.2%	0.2%	0.2%	0.2%	15.6%	0.2%
	CRAN(70%)	0.6%	0.6%	0.7%	0.6%	117.6%	0.4%
	DRAN-8	1.3%	1.4%	3.3%	1.3%	26.0%	1.5%
	CRAN-8(70%)	6.5%	5.8%	3.7%	5.9%	415.3%	1.7%
	DRAN-16	2.6%	2.8%	6.3%	2.6%	43.8%	2.8%
	CRAN-16(70%)	13.2%	11.9%	6.7%	12.0%	716.2%	3.0%

Table VI shows the resources required for an LR-PON deployment with only wired customers connected. It then also reports on the additional resources (in %) for a deployment with only DRAN cells and for a deployment where all feasible sites are centralised following the CRAN architecture. In this case there are roughly 65% CRAN feasible cells, c. f. Table V.

We can clearly observe that the increase in required resources for wireless integration compared to existing LR-PONs connecting all households is insignificant. Even in case of a CRAN deployment the number of PONs increases only by 1.14% (0.16% for DRAN only). Notice that almost all LEs have a connected site in our solution for the UK. This means that if DRAN cells where integrated into PONs independent of PONs for wired customers, then the number of additionally required PONs would be at least 5,449 (the number of LEs). However, we only need 120 additional PONs for DRAN deployment (0.16%). This means that most of the required DRAN ports could be integrated into the existing residential PONs. The same holds for the CRAN deployment. Since the number of PONs does not increase significantly also all other numbers have relatively moderate increases (splitters and fibre resources) as well. This shows that wireless convergence in LR-PONs is feasible with very low impact compared to the fixed access LR-PON deployment, both in CRAN and DRAN.

The only number that increases significantly in Table VI is the number of OLTs. For the DRAN deployments it increases by 8% while for CRAN deployment it increases by even 115%. Recall that residential customer PONs only occupy one colour of the WDM PON while 32 DRAN sites already require its own colour and each sector in the CRAN deployment.

It further turns out that these observations are relatively independent from the actual country and MC node distribution. In Table VII we summarise the results for the different countries. We also tested solutions with a much larger MC node density (not reported in the table) and we did not observe any difference in the DRAN deployment even when the number of MCs increases drastically (we tested up to 600 MCs in the UK). However, with increasing MC node numbers the CRAN coverage increases which results in a moderate increase of the number of PONs and the corresponding resources for CRAN.

It can be also be observed in Table VII that the distribution of LEs and antenna sites is such that for Spain and Italy even more DRAN and CRAN cells can be integrated into the wired PONs (the supplemental PON numbers are very small). In fact, the number of cells for the UK is relatively large compared to the UK area and compared with Spain and Italy, which is mainly due to a higher population density in some areas and the resulting large number of (Dense) Urban sites, see Table IV.

We also studied a micro cell scenario where 8 or 16 small cells are deployed in addition to the macro site (except for Sparse Rural sites), also reported in VII (rows: DRAN-8, CRAN-8, DRAN-16, CRAN-16). The micro cells are assumed to have one sector only and are treated similar to macro cells in terms of required resources. While the increase in additionally required resources is still moderate in the DRAN case, it is significant for CRAN, in particular in the 16 micro cell scenario. The number of PONs increases by 11.7% to 16.2%, which results in a significant increase of the corresponding resources such as cabling in ODN and backhaul and the number of splitters. We note that with an increase of 10% and more of the fibre resources we can also not longer ignore the additional cost for duct build. Clearly, the increase of cable kilometres is less than the increase in fibre kilometres, e.g. the 12.8% increase in the feeder for the UK solution refers to an increase of only 5.2% in required cables. The cables simply contain more fibres. However this effect is not as significant in the ODN and absent in the Drop section (1-fibre cable). We further note that if the duct build probability depends linearly on the number of cables an a trail, then the additional duct build in percent will be identical to the additional cable resources in percent, e.g. 5.2% in the feeder area.

VII. COST CONSIDERATIONS

So far we ignored the notion of cost. In particular, we ignored the cost for the actual antenna sites. To get an idea of the cost difference for DRAN versus DRAN deployments we use the techno-economical model summarised in Table VIII. Cost values are given in relation to the cost for one OLT port, which has a cost of 1.0. We assume that by centralising we can save 50% operational and 20% capital expenditures, that is, the cost for a CRAN RRH plus the share at the centralised BBU is 80% of the cost of a DRAN macro site.

TABLE VIII. HARDWARE AND COST MODEL FOR LR-PON, CRAN, AND DRAN DEPLOYMENT. COST VALUES ARE GIVEN RELATIVE THE COST OF ONE OLT PORT. CRAN SITE COST INCLUDES THE COST FOR THE RRH AND THE BBU SHARE.

Entity	DRAN	CRAN
OLT port	1.00	1.00
ONU port	0.04	0.03
Macro site (RRH plus BBU share)	6.42	5.13
Opex per macro site per year	11.43	5.72
Cable kilometre ODN 8 fibres	0.38	0.38
Cable kilometre Drop 1 fibre	0.07	0.07
Cable kilometre feeder 48 fibres	1.05	1.05
...	...	...
Cable kilometre feeder 276 fibres	2.62	2.62
4x4 splitter and amplifier	2.39	2.39
1x16 splitter	0.28	0.28
1x8 splitter	0.18	0.18

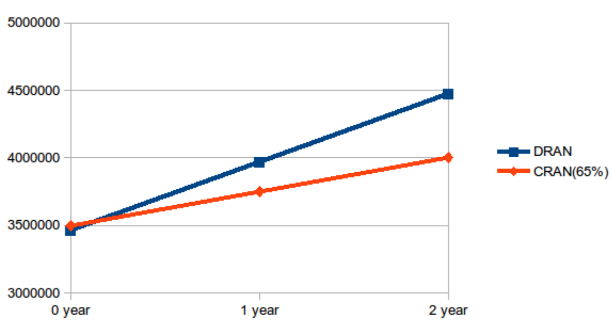
Based on this cost model we can easily evaluate the total cost for the LR-PON deployments in Table VI. For the UK solution with 73 MCs we compute an up-front cost investment for wireline integration of 3 Mio OLTs (ignoring duct cost). In Table IX it can be seen that most of this cost is consumed by ONUs and cable resources in the ODN/Drop. The increase in cost for wireless integration is moderate if only macro cells are considered. For DRAN we pay 11,155 and for CRAN 103,801 OLT units. Most of this increase is in the OLT cost, 5,602 for DRAN and 85,408 for CRAN. The second largest absolute increase is in the total cost for cabling (Feeder plus ODN plus

TABLE IX. DRAN AND CRAN DEPLOYMENT AND REQUIRED ADDITIONAL CAPITAL EXPENDITURES COMPARED TO PURE RESIDENTIAL LR-PONS (BASE) – UK INSTANCE – BASE COST VALUES ARE GIVEN W.R.T COST OF ONE OLT PORT. – WE REPORT ON THE MACRO CELL DEPLOYMENT AND A DEPLOYMENT WITH 16 ADDITIONAL MICRO CELLS PER MACRO CELL.

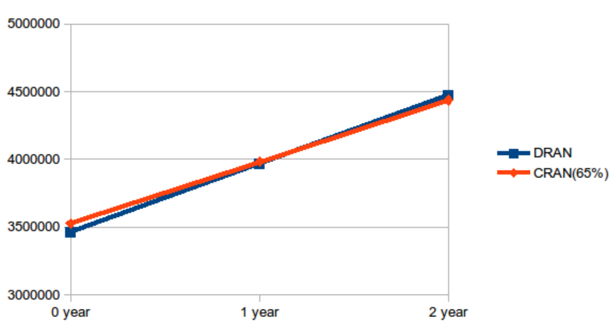
		Supplement			
Entity	Base	DRAN	CRAN (65%)	DRAN-16	CRAN-16(65%)
Feeder Cable	190,310	0.14%	0.66%	1.61%	8.91%
ODN Cable	107,433	0.42%	1.26%	6.93%	7.77%
Drop Cable km	968,341	0.21%	0.64%	6.41%	6.84%
Amplifier nodes	177,982	0.16%	1.14%	2.41%	16.23%
Cabinet splitter	53,566	0.16%	0.16%	2.41%	2.41%
DP splitter	351,551	0.16%	1.14%	2.41%	16.23%
ONUs	1,174,957	0.15%	0.30%	2.54%	2.47%
OLTs	74,397	7.53%	114.80%	36.49%	716.87%
Total	3,098,536	0.36%	3.35%	4.63%	18.43%

Drop). Recall that our numbers for the Feeder are accurate estimations based on real fibre routes and a cable model with different cable sizes. We do not expect a significant increase in the cost for ducts for wireless macro cell integration. In fact, assuming a duct build probability of $n \cdot 3\%$, where n is the number of cables on a trail, we estimate a duct base cost of 67,800 OLTs (in addition to the 3 Mio up-front cost) in the feeder area, which increases by only 56 for DRAN and 275 for CRAN.

In Table IX we ignore both the capital expenditures and the operational expenditures for the antenna sites itself. We have 44,309 macro sites, which results in an investment of 284,316 (DRAN) or 227,453 (CRAN), that is, we save 56,863 with CRAN. However already the increase in the OLT cost exceeds these savings. Considering the pure total investment (LR-PON cost plus site cost) a CRAN solution for the UK costs 36,079 more than a DRAN solution. However, this is not a huge difference and since CRAN outperforms DRAN in terms of operational cost (50% savings assumed), CRAN amortises already in the first year (compared to DRAN, see Fig. 9(a)). If we decrease both the capital and operational savings by centralising to only 10% per site CRAN still amortises already in the second year, see Fig. 9(b).



(a)



(b)

Fig. 9. Additional capital and operational expenditures of wireless integration including LR-PON resources and antenna sites. UK instance. a) capital/operational expenditures as in Table VIII b) capital/operational savings per site by centralising only 10%.

VIII. Conclusion

In this paper we studied wireless integration into an access architecture based on long-reach passive optical networks and WDM. We showed that wireless/wireline convergence is feasible as the supplement in required resources to include antenna sites is marginal. This is in fact independent of whether DRAN or CRAN approaches are considered. Clearly, it is advisable to reserve capacities already when deploying PONs for wired clients. With CRAN we observe a significant increase in the number of required OLTs, which is larger than the capital savings at the antenna site. However since centralising should provide enormous savings in the operational cost, we could show that CRAN amortises already in the first years after the deployment compared to DRAN. The picture changes and needs further studying if there is a significant portion of micro cells deployed and integrated into the PON. In this case even additional duct build might be necessary.

Acknowledgement

To authors would like to thank Thomas Pfeiffer and Rene Bonk for many fruitful discussions regarding wireless integration. We would also like to thank Marco Schiano and Andrew Lord for providing realistic data from Telecom Italia and British Telecom.

References

[1] "DISCUS (FP7 Grant 318137), Deliverable 2.3, Updated reference architecture," 2014.

[2] M. R. et al., "Discus: An end-to-end solution for ubiquitous broadband optical access," *IEEE Com. Mag.*, vol. 52, no. 2, 2014.

[3] "40-Gigabit-capable passive optical networks (NG-PON2): General requirements," ITU-T, Series G: Transmission Systems and media, digital systems and media, Tech. Rep. G.989.1, 2013.

[4] "DISCUS (FP7 Grant 318137), Deliverable 4.2, System specifications for LR-PON implementation ," 2014.

[5] C. Raack, N. Ascheuer, and R. Wessäly, "A nation-wide optimization study on the consolidation of local exchanges using long-reach passive optical networks," in *Proc. ICTON, Graz, Austria*, 2014, pp. 1–5.

[6] ——, "Nation-wide deployment of (long-reach) passive optical networks: Computing the location and number of active nodes." in *Proc. ITG Fachtagung, Leipzig, Germany*, 2015.

[7] OSM, "Open Street Maps, http://www.openstreetmap.org," 2015.

[8] "DISCUS (FP7 Grant 318137), Deliverable 2.6, Architectural optimization for different geo-types," 2014.

[9] L. C. Wang, K. Chawla, and L. J. Greenstein, "Performance studies of narrow-beam trisector cellular systems," *International Journal of Wireless Information Networks*, vol. 5, no. 2, pp. 89–102, 1998.

[10] J. Itkonen, B. Tuzson, and J. Lempiäinen, "Assessment of Network Layouts for CDMA Radio Access," *EURASIP Journal on Wireless Communications and Networking*, vol. 2008, no. 259310, 2008.

[11] M. U. Sheikh and J. Lempiäinen, "A flower tessellation for simulation purpose of cellular network with 12-sector sites," *IEEE, Wireless Communications Letters*, vol. 2, no. 3, pp. 279–282, 2013.

[12] M. Shimrat, "Algorithm 112: Position of point relative to polygon," *Communications of the ACM*, vol. 5, p. 434, 1962.

[13] B. Guo, W. Cao, A. Tao, and D. Samardzija, "LTE/LTE-A signal compression on the CPRI interface," *Bell Labs Technical Journal*, vol. 18, no. 2, pp. 117–133, 2013. [Online]. Available: http://dx.doi.org/10.1002/bltj.21608

[14] P. Chanclou, A. Pizzinat, F. Le Clech, T.-L. Reedeker, Y. Lagadec, F. Saliou, B. Le Guyader, L. Guillo, Q. Deniel, S. Gosselin, S. Le, T. Diallo, R. Brenot, F. Lelarge, L. Marazzi, P. Parolari, M. Martinelli, S. O'Dull, S. Gebrewold, D. Hillerkuss, J. Leuthold, G. Gavioli, and P. Galli, "Optical fiber solution for mobile fronthaul to achieve cloud radio access network," in *Future Network and Mobile Summit (FutureNetworkSummit), 2013*, July 2013, pp. 1–11.