PROJECT FINAL REPORT

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Final publishable summary report

Executive Summary

To enjoy sustainable economic and social benefits, it is of utmost importance that advanced broadband networks and applications are available to all European business and consumers according to the European growth strategy Europe 2020. This is in line with the ambitious high-speed targets of the Digital Agenda for Europe (DAE) aiming to assure „comprehensive availability and take-up of fast and ultra-fast internet“ to each European.

Fiber, in particular point-to-point fiber development, is the most “future proof” network technologies to reach the above targets and deliver next generation access. However, recently the Communications Committee reported to the EC that Europe is only halfway to achieve its objective of making at least 30 Mbit/s broadband available to all homes by 2020. Even worse, in 2013, 35 million of the 40 million rural homes, i.e. almost 90% of all rural homes in the EU are still waiting for next generation access (NGA) to arrive. This is since next generation access (NGA) technologies have a low share in fixed broadband lines. The FTTx roll-out and capex in developed economies forecast report for 2012-2017 by analysis mason clearly shows that in terms of mature telecom markets, Europe lag far behind developed Asia-pacific regions. The reason is seen in the risk in investment in the highly regulated NGA infrastructure in the EU, which led to the fact that NGA technologies still have a low share as recently ascertained in the Communications Committee report.

In IPHOBAC-NG, in 2013, we proposed a technical solution for accelerating the deployment of fast internet access solutions. We are aimed at developing application-specific lasers, optical modulators and detectors to construct novel optically supported millimeter-wave wireless systems for providing a) complementary broadband 1-10 Gbit/s fixed wireless access (FWA) and b) 3 Gbit/s wireless backhaul for mobile networks; both being seamlessly integrated in next generation optical access (NGOA) networks based upon a WDM-PON infrastructure.

For socioeconomic reasons, IPHOBAC-NG also aimed at integrating its wireless technology in legacy GPON networks because they are widely available in Europe.

What has been forecasted by the IPHOBAC-NG consortium in 2013 has become reality by now. As of today, FWA has become a commercially valid alternative especially in the United States but also elsewhere, for providing internet access to homes using wireless mobile network technology rather than fixed lines.

Moreover, the IPHOBAC-NG FWA approach which was based upon using the millimeter-wave spectrum is now widely accepted and it is anticipated that the next stage of FWA will utilize 5G network technology, such as beam-forming and a high-frequency millimeter-wave spectrum, to provide a considerable performance boost to wireless broadband services.

In IPHOBAC-NG, we not only successfully developed and integrated fully transparent and optically supported radio access units (RAU) operating in the 57-64 GHz as well as 71-76 GHz and 8-86 GHz spectrum. The developed RAU have also been successfully exploited for providing FWA and mobile fronthaul/ backahaul. World record spectral efficiencies of 10 bit/s/Hz per antenna and ultrafast wireless link data rates in excess of 20 Gbit/s per antenna were demonstrated in IPHOBAC-NG. Furthermore, the developed RAU were successfully implemented in a real-word network of ORANGE for bridging a standard 2.5 Gbit GPON lines wirelessly.

Project scope and objectives

To enjoy sustainable economic and social benefits, it is of utmost importance that advanced broadband networks and applications are available to all European business and consumers according to the European growth strategy Europe 2020. This is in line with the ambitious high-speed targets of the Digital Agenda for Europe (DAE) aiming to assure „comprehensive availability and take-up of fast and ultra-fast internet“ to each European. Key targets of the DAE referring to broadband coverage are:

- All homes should have access to high-speed broadband of at least 30 Mbit/s by 2020

Fiber, in particular point-to-point fiber development, is the most “future proof” network technologies to reach the above targets and deliver next generation access. However, recently the Communications Committee reported to the EC that Europe is only halfway to achieve its objective of making at least 30 Mbit/s broadband available to all homes by 2020. Even worse, 35 million of the 40 million rural homes, i.e. almost 90% of all rural homes in the EU are still waiting for next generation access (NGA) to arrive. This is since next generation access (NGA) technologies have a low share in fixed broadband lines. The FTTx roll-out and capex in developed economies forecast report for 2012-2017 by analysis mason clearly shows that in terms of mature telecom markets, Europe lag far behind developed Asia-pacific regions. The reason is seen in the risk in investment in the highly regulated NGA infrastructure in the EU, which led to the fact that NGA technologies still have a low share as recently ascertained in the Communications Committee report.

In IPHOBAC-NG, we proposed a technical solution for accelerating the deployment of fast internet access solutions. We are aimed at developing application-specific lasers, optical modulators and detectors to construct novel photonic millimeter-wave radios (PMWR) for providing a) complementary broadband 1-10 Gb/s fixed wireless access and b) 3 Gb/s mobile backhaul; both being seamlessly integrated in next generation optical access (NGOA) networks based upon a WDM-PON infrastructure. For socioeconomic reasons, we also aimed at integrating our PMWR in legacy GPON networks because they are widely available in Europe.

The strategic technical objectives of the IPHOBAC-NG project are visualized at a glance in Figure 1. The key objective was to develop novel integrated radio access units (RAU) interfacing future high-capacity optical dense WDM passive optical networks (WDM-PON) with 70/80 GHz (E-band) wireless links providing a fiber-extension for backhauling applications. The novelty in the RAU concept is the proposed coherent approach that allows seamless integration in real-life networks.

The key expected advantage is that the proposed RAU is designed for integration in a real-life network.

For the development of the coherent RAU, the project developed new integrated InP lasers, photonic locking schemes, novel mm-wave single-sideband GaAs modulators, novel mm-wave coherent InP photonic mixers (CPX) for coherent heterodyne detection and new SiGe amplifiers operating at 70/80 GHz. All these technological activities were complemented by several actions yielding in new packages for such components.

From a technical management point of view, the IPHOBAC-NG objectives were truly challenging. The project’s aim was not just to develop new technology and new prototype modules but also to implement and test these new photonic prototypes in real-world networks.

In other words, the IPHOBAC-NG project targeted at technological developments at TRL level 1 and to bring them up all the way to system prototype demonstration in real-world networks, i.e. TRL level 7.

These technological and technical activities were supported by several disseminations, standardization and exploitation activities.

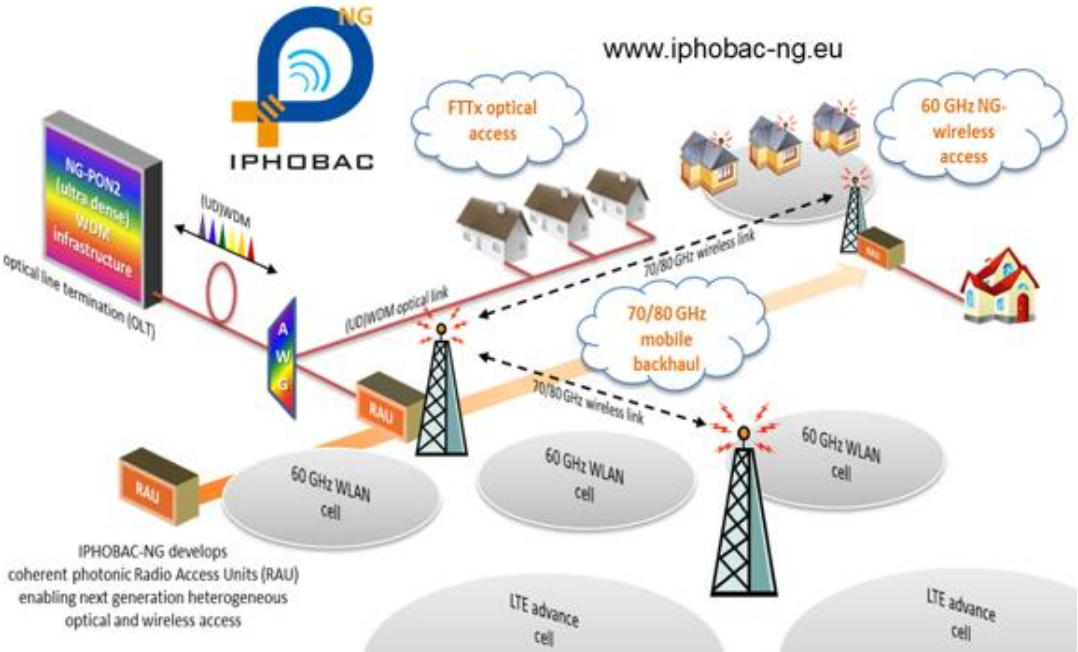


Figure 1: Strategic objectives of IPHOBAC-NG at a glance

Because of some delays in laser and modulator fabrication and packaging, the consortium had asked for an extension of the project duration from originally 36 months to now 39 months.

Overall, the project execution was divided into six work packages (WP). The execution of the work packages are illustrated in the revised Gantt chart in *Figure 2*.

The chart includes the project extension of three months.

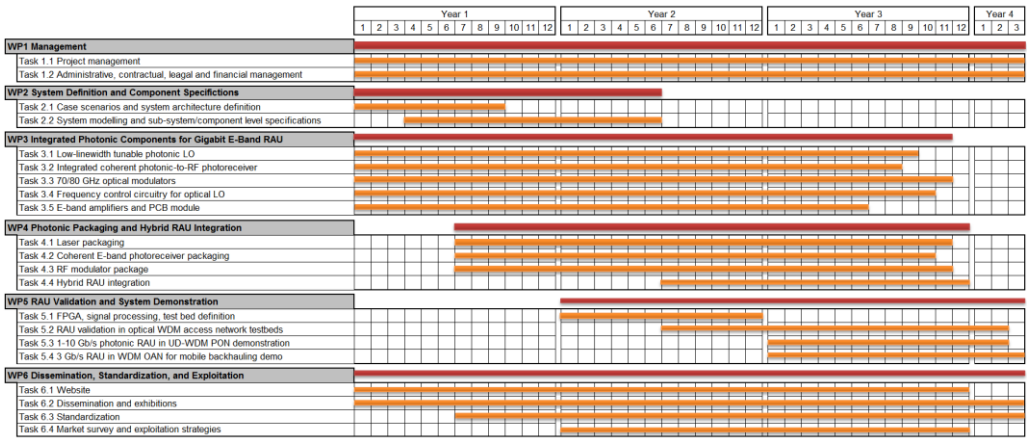


Figure 2: Task execution at a glance – Gantt chart.

The key objectives of the six work packages were as follows:

All legal, financial and management activities were carried out in WP1.

System scenario definition, system specifications and component modelling/ specifications were carried out in WP2 for guiding the technological activities and the test bed definition.

The application-specific photonic components and the mm-wave electronic components for the integrated RAU were developed in WP3. The key challenge of WP3 were to achieve component performances beyond the SotA with a high level of integration and functionality.

WP4 focussed on the development of the advanced photonic packages. The packaged integrated photonic modules were then used for the development of the Gigabit E-band RAUs for validation in real-world demonstrations in WP5.

Exploitation, standardization and dissemination activities were carried out in WP6.

The key technical/ technological objectives for each WP were as follows:

WP2: The overall objectives of WP2 (led by UCL) were:

- T2.1 case scenario and system architecture descriptions (ORANGE),
- T3.2 subsystem and component specifications (DTU).

WP3: The key objectives of WP3 (III/V-LAB) covered the technological fabrication of the lasers, modulators, photodiodes, RF submounts and RF amplifiers. Another objective was the test of the chips in laboratory set-ups and the provision of chips for module packaging to WP4.

The key objectives on the task level were:

- T3.1 Technological fabrication of the low-linewidth photonic LO (laser with integrated PD) and provide chips for packaging to WP4 (III/V-LAB)
- T3.2 Fabrication and testing of single type and balanced photodiode chips. Finish fabrication of the RF submounts for photoreceiver module fabrication. Provide chips for photoreceiver module packaging to WP4.
- T3.3 Fabrication of the 70/80 GHz optical modulator chips and provide chips for module packaging to WP4 (AXENIC)
- T3.4 Development and testing of the frequency control system for LO control for laboratory system-level tests
- T3.5 Fabrication of the E-band amplifiers SiGe chips and PCB integration submounts and provide integrated amplifier chips to packaging in WP4 (SIKLU).

WP4: The key objectives of WP4 (led by FINISAR) were to package designs for the different components to be used in the coherent RAU based on initial component specifications coming from WP2. Due to the delay in laser and modulator fabrication, additional frequency-agile laser development (UDE), testing of a commercial 110 GHz modulator (UDE). Also, a novel hybrid integrated RAU for the planned GPON field trial at ORANGE facilities (UDE) were also developed.

The key objectives for the reporting period on the task level were:

- T4.1 Packaging of the frequency-agile low-linewidth laser chips from T3.1 (III/V) and develop frequency-agile low-linewidth laser modules using commercial ECL laser chips (UDE). Provide lasers (III/V and UDE) for lab tests and field trials to partners.
- T4.2 Packaging of the different coherent E-band photoreceiver designs; a V-type photoreceiver module w/o amplifier and a WR12-type with integrated amplifier (UDE/FINISAR). Test photoreceiver module using laboratory set-ups (UDE/FINISAR), provide and test photoreceiver modules for the GPON field trial (UDE/FINISAR).
- T4.3 Packaging of the single-sideband RF modulators and provide packaged modules for lab test and field trials to partners (AXENIC).
- T4.4 Integration of the hybrid RAU and provide the hybrid RAU for field trials after laboratory testing (SIKLU and UDE)

WP5: The key objectives of WP5 (ORANGE) were focusing on FPGA developments and the definition of the test beds all within task 5.1. Further activities were to test the hybrid RAUs in laboratory test (task 5.2 and task 5.3) as well as in a real-world GPON field trial (task 5.4).

The key objectives for the reporting period on the task level were:

- T5.1 within this task, DTU proposed different test bed scenarios for the RAU developed in IPHOBAC-NG. These tests include RF component level tests, RF related system level tests, and testbed in PON scenarios. The scenarios are designed to assess the lower and upper boundaries in terms of operability of the RAU.
- T5.2 within this task, UCL performed optical WDM experiments using the hybrid integrated RAUs.
- T5.3 within this task, UDE constructed a hybrid optical ultra-dense WDM laser source using commercially available external-cavity laser diode modules. This has been decided among the partners to be necessary for allowing early system level validations as a contingency plan for laser diode chip (task 3.1) and laser package (task 4.1) developments. Using this new optical ultra-dense WDM laser source, UDE successfully performed first experimental validation testsof the hybrid integrated RAU in an ultra-dense WDM PON network and a legacy GPON network (in cooperation with ORANGE).
- T5.4 within this task, ORANGE performed a GPON wireless extension field trial at its facilities in Garwolin, Poland (in close cooperation with UDE, SIKLU and FINISAR).

WP6: The key objectives of WP6 (UDE) were to increase the awareness of the technologies capabilities by various dissemination activities and especially to support the rapid exploitation of the knowledge and the technological developments gained in the project in industrial products and systems. To support these exploitation strategies, IPHOBAC-NG partners were actively participating in standardization actions, performed market surveys and exhibited the IPHOBAC-NG's technological developments at international fairs. The main planned activities in WP6 for the reporting period are:

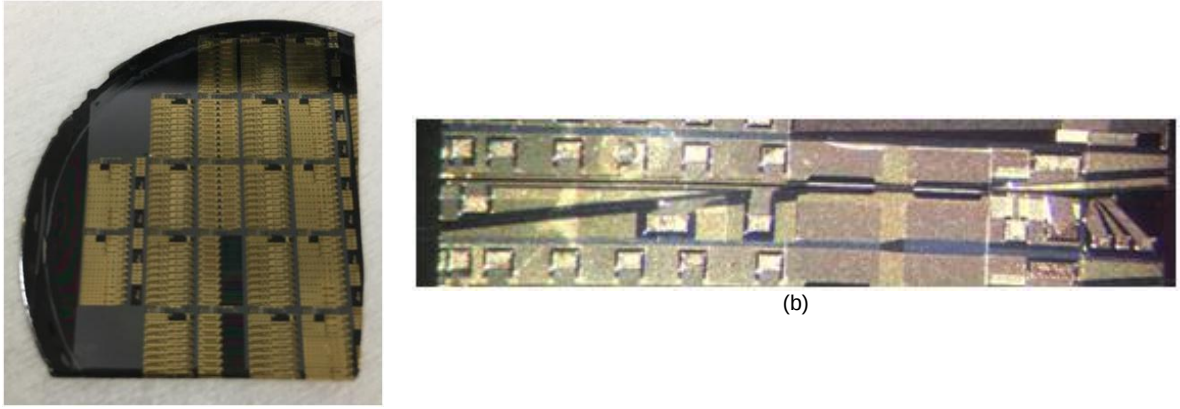
The key objectives for the reporting period on the task level are:

- T6.1 Reporting of the IPHOBAC-NG dissemination activities and coordinating the IPHOBAC-NG exhibitions (UDE)
- T6.2 Coordinating the individual standardization activities of the IPHOBAC-NG partners (ORANGE)
- T6.3 Developing a market survey and exploitation strategy for the IPHOBAC-NG technologies (FINISAR)

Main S&T achievements

Low-linewidth tunable photonic LO (led by III/V Lab)

III/V-Lab has been working on the fabrication of photonic integrated circuits with a tunable narrow linewidth DFB laser, optical amplifiers, passive optical combiners and splitters, an electro-optical modulation section and a high-speed photodiode. Pictures of the wafer after process are presented in Figure 3.



(a) (b)

Figure 3: (a) Wafer after process and (b) view on one of the devices from the wafer.

Two devices coming from a fabrication carried in the frame of the iPHOS project have been tested and delivered to UCL, so the planned laboratory tests could be performed despite the absence of the expected devices.

Integrated coherent heterodyne photoreceiver (led by UDE)

Optimized 80 GHz triple transit region photodiode (TTR-PD) chips and the optimized 70/80 GHz RF-laminates, were both developed by UDE. The successful fabrication of optimized TTR-PD chips (from the second run at UDE) and the related on-chip RF characterization within the 70/80 GHz band and beyond were introduced in D322. The DC responsivity of >0.4 A/W was attained for the TTR-PD chips (without anti-reflection coating). In addition to that, device operation up to 190 GHz was achieved, as shown in *Figure 4*.

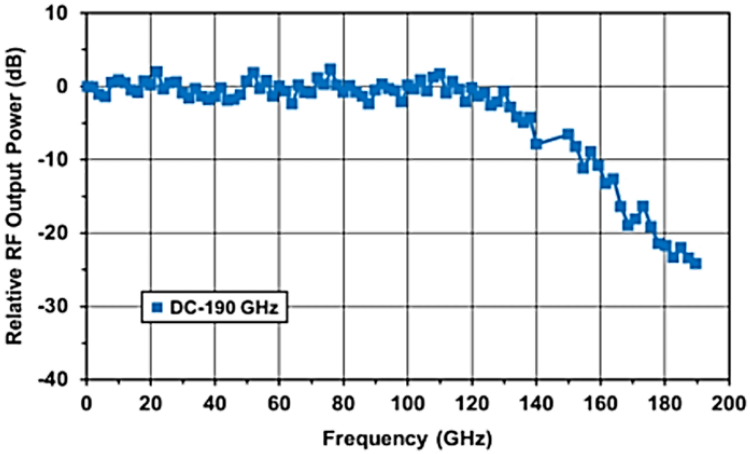


Figure 4: Relative frequency response of a TTR-PD chip from the second UDE run up to 190 GHz.

Further, optimized RF-submounts based on laminates were introduced in D322, enabling biasing, RF-amplifier integration, as well as WR-12 coupling. Here, an optimized compact fully-planar 71-76 GHz and 81-86 GHz laminate-based GCPW to WR-12 transition (4.8 x 5.5 mm^2) was designed, simulated, and fabricated on a 127 µm thick ROGERS RT/duroid 5880 laminate, as shown in Figure 5, making use of the double-slot antenna approach presented in MS421.

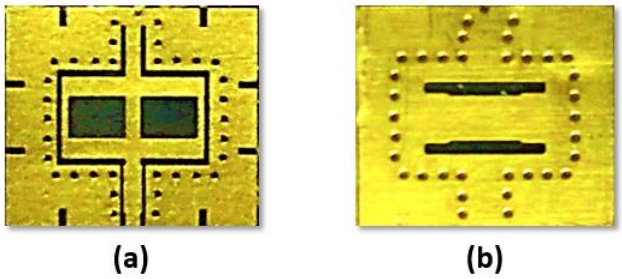


Figure 5: Top view (a) and bottom view (b) of the optimized and fabricated conductor-backed coplanar waveguide to hollow metallic waveguide transition showing the double-slot antenna structure.

<u>70/80 GHz optical modulators (led by AXENIC)</u>

GaAs/AlGaAs SSB modulators have been realized (by AXENIC) and tested (by UCL) up to 67 GHz. The dual-parallel Mach-Zehnder (MZ) configuration uses a straight-in RF layout with a folded optical path, as described in the reports D332 and D333. CPS and CPW variants in two design/fabrication phases have been assessed, initially mounted on open carriers using RF probing and micro-manipulated optical fibers. This work ascertained that while the RF loss was at about the expected level, the RF velocity was consistently higher than that been calculated for the design. The traveling-wave design is critically dependent on achieving an accurate velocity match between the light and the microwave traveling along the modulation electrodes, and at E-band there is little room for error. Though small in absolute terms, the velocity-match error is significant and has the effect of up-shifting the match-frequency (and response peak) out of band. The open-carrier, RF-probed measurement is shown in Figure 6.

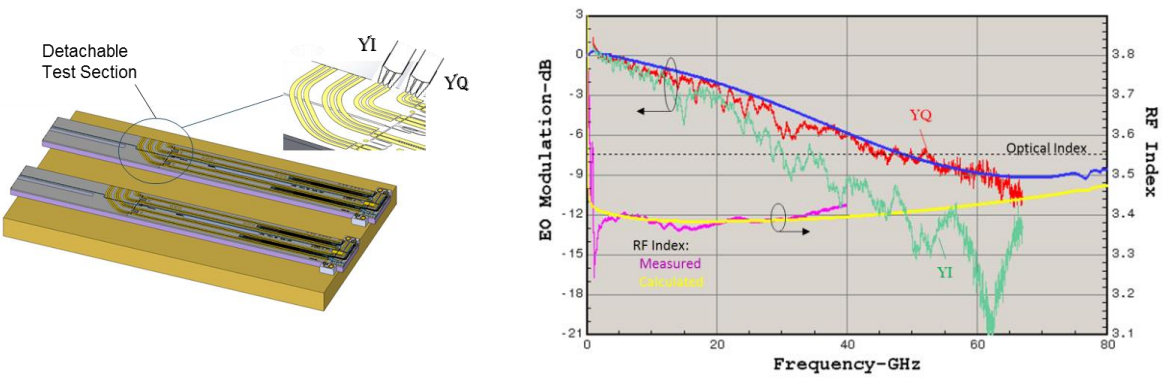


Figure 6: Modulator chip-on-carrier (CoC) configuration and result. The detachable 90° RF bends are removed for packaging. Blue and yellow curves are from simulation.

<u>Frequency control circuitry for optical LO (led by UCL)</u>

In this task, the electronic circuit for optical phase lock loop (OPLL) has been designed based on a dual-balanced mixer, variable gain amplifier and phase detector. Each of these components has been characterized separately, and when assembled together will allow to frequency and phase stabilize a semiconductor laser with up to 65 GHz frequency offset from the optical reference carrier. The total phase error propagation delay in the feedback loop was estimated to be about 2.4 ns. The OPLL with such a delay is suitable to phase lock the laser with the FWHM linewidth of less than 1.2 MHz. The power of the heterodyne signal at the output of the integrated photodiode should be greater than -30 dBm at offset locking frequency. A detailed design of the 65 GHz optical phase lock loop has been included in the D342 report.

The integrated laser was successfully phase stabilized in respect to the reference optical tone with the adjustable frequency offset of up to 12 GHz. The spectra of the phase stabilized and free running heterodyne signal are presented on Figure 7, demonstrating the difference in linewidth and peak power of the free running and locked beat note signals at ~8 GHz.

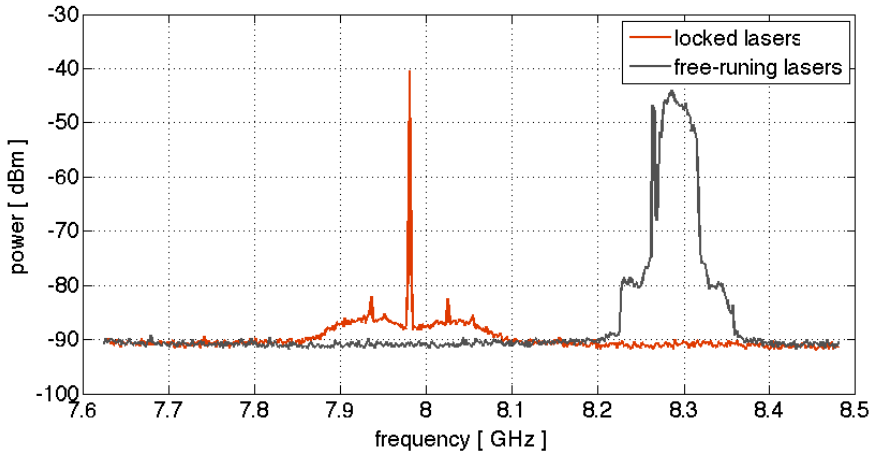


Figure 7: Electrical spectra of the phase locked and free running heterodyne signal: RBW = 300 kHz, VBW= 30 kHz, SWT=0.09 s. Measurements present 50 sweeps in max-hold trace mode.

The frequency difference between the two lasers is limited to 12 GHz predominantly due to the bandwidth of the integrated PIN photodiode and can be increased if the PIC with greater bandwidth photodiode becomes available. To further assess the quality of phase locking, the single-sideband phase noise spectra of the heterodyne signal were measured revealing the phase noise reduction to below –100 dBc at 10 kHz frequency offset from the carrier as described in D342.

<u>E-band amplifiers and PCB module (led by SIKLU)</u>

In this task, the performance specification of the PA and LNA block has been fully defined based of the final specification of the optical components, and an LNA and PA PCB and housing has been design to make use of the SiGe amplifier as the main amplification block. Both PCBs have been manufactured, assembled and characterized. This activity has been reported in deliverable D352.

The amplifiers have met the design targets for gain, dynamic range and noise-figure that were required to meet the system specification. Valuable lessons and conclusion were learned from the integration process as summarized in D352.

Table 1: Table of main technological project innovations (WP3), as well as expected and achieved outcomes.

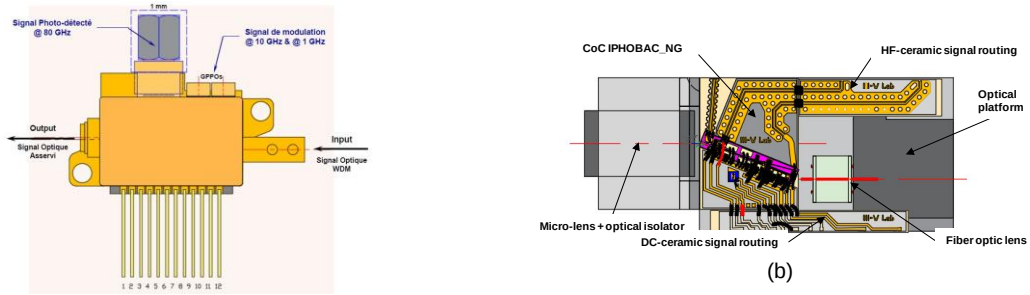
Photonic components and sub-system performances (WP3)		
Ultra-narrow linewidth tunable ECL laser	Targeted performance specification	Achieved performance specification
Optical wavelength:	1.5 µm	~ 1,53-1,57
Output power:	max. +13 dBm	max. +16 dBm
Tuning range:	3 nm	~ 40 nm
Spectral linewidth:	< 100 kHz	< 300 kHz (meas.), ~ 100 kHz (expected)
Single-sideband optical modulators	Targeted performance specification	Achieved performance specification
Optical wavelength:	1550 nm	1490 – 1580 nm Loss minimum at: 1500nm 1st pass design 1545nm 2nd pass design
Operating frequency:	70-80 GHz final 60GHz demonstrator	> 67 GHz. (See 3.3 and 4.3)
Insertion loss: (Package Dependent – see 4.3)	< 10 dB	Typ. 10 dB at 1550 nm 8.5 dB at 1520 nm
DC Vπ:	3 – 4.35V variant dependent	On-target within 5% e.g. 2.87V for 3V variant
RF Vπ (Package Dependent – see 4.3)	< 10V at band center	<7.5 V at 65 GHz (3V variant)
Optical Extinction Ratio	>24 dB	>25 dB
Optical Interface	Folded. Single-ended optical I/O	Verified low loss-penalty from path-folding.
RF Interface	Straight, in-line RF inputs	Extended response verified for in-line inputs.
High output-power integrated coherent heterodyne photoreceiver (only PD chip)	Targeted performance specification	Achieved performance specification
Optical wavelength:	1.5 µm	~ 1.55 µm
Output power (only PD):	> 0 dBm @ 70/80 GHz	> 0 dBm @ 70/80 GHz
Output power of photoreceiver:	> 15 dBm @ 70/80 GHz	see WP4
Flatness (only PD):	+/- 1.5 dB	+/- 1-2 dB
Photodiode bandwidth:	5 GHz (71-76 GHz, 81-86 GHz)	> 100 GHz (3 dB BW), < 190 GHz (operat. BW)
Responsivity (only PD):	> 0.5 A/W	> 0.4 A/W (meas. w/o ARC), > 0.5 (expected w/ ARC)
Amplifier chip	Targeted performance specification	Achieved performance specification
Operation band	71-76 GHz	71-76 GHz
Temperature range	-40 – 85 C°	-40 – 85 C°
Gain	40 dB	>39 dB
Gain control	0 to full gain	0 to full gain
P_{SAT}	15 dBm	>15 dBm
P_{1dB}	12 dBm	>12 dBm

Laser packaging (led by III/V Lab)

The modules that were to be delivered within the IPHOBAC-NG project are of two types:

- A single narrow linewidth DFB laser that has been delivered during the first period,
- A narrow linewidth DFB laser integrated with an optical input, optical couplers, optical amplifiers and a high speed photodetector.

In a first time, a mechanical and RF design work has been done in order to get an assembly that is able to handle the two optical ports (one input and one output), the millimeter wave output, the two HF inputs and the numerous DC bias connections. The corresponding drawings are presented in Figure 8.



(a) (b)

Figure 8: Pictures of the design (a) of the modified butterfly case, (b) of the optical and HF assembly.

The different HF elements have been tested and had performances meeting the requirements. As no devices could be obtained from the fabrication run of task 3.1, the final assembly has not been done. As soon as devices are coming from the planned fabrication run, we plan to place them in modules using this assembly. All the design, fabrication and element characterization work is described in deliverable D412.

Coherent E-band photoreceiver packaging (led by FINISAR)

After the work of the first part of the project concentrated on the packaging of the photoreceiver alone, i.e. without an integrated low-noise amplifier (LNA) in the same package, in the second part of the project exactly this was done: a coherent mixer module with commercial electrical low-noise amplifier (LNA) was developed. The module was based on the same Kovar gold-box package with standard fiber-feedthrough and an internal submount for the assembly of the o/e and electrical chips, DC- and RF-ceramics and the fiber-chip coupling.

The module consists of a standard package with 16 DC-pins and a dual-fiber feedthrough with SMF-28 fiber, as it is used for several other Finisar products. The major difference is the rectangular waveguide port at the bottom of the package, instead of the standard coaxial RF connector, like V- or GPPO connector.

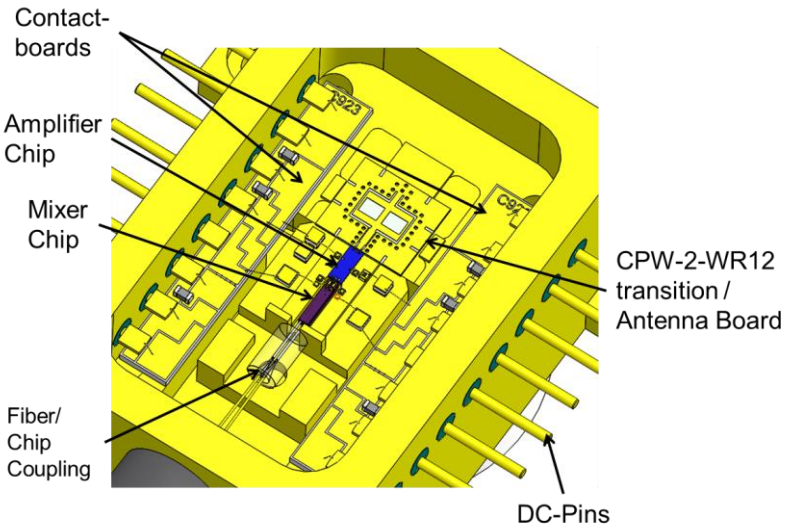


Figure 9: Coherent mixer package design.

Inside the module, the layout is pretty similar to the first version with amplifier inside. It consists of a submount with DC-ceramics, a fiber/chip coupling wall and a plateau to mount the mixer and now additionally the amplifier (LNA) chip. Now the amplifier is wire bonded to the CPW to WR12 transition and the antenna structure. These are used to irradiate the RF-signal into the rectangular waveguide port; in this case a WR12 waveguide. The InP mixer and LNA chips are placed on the submount and the ROGERS laminate contains the CPW to WR12 transition with integral antenna structure (see Figure 9).

For these new modules with amplifier the CPW to WR12 transition and antenna structure have undergone some minor changes as well. This allowed to better match the mechanical dimension of the rf-output of the amplifier chip and the ROGERS laminate as well as to slightly shift the pass band behavior of the structure towards higher frequencies.
UDE did then deliver the processed ROGERS WR12 Antenna (CPW-2-WR transition) and the used LNA amplifier to FINISAR for the second run of the coherent mixer packaging.
After the new module concept was finished and all revised components designed and manufactured, we started with the assembly of the second batch of detector modules with WR-output, this time with additional electrical amplifier inside. Apart from a few new adapter boards and submounts to hold the chips and secure the WR-output, existing processes and assembly machines / stations could be used for the die attach, wire-bonding and fiber/chip coupling processes. Pictures of the first finished coherent mixer module with amplifiers are shown in Figure 10 and Figure 11.

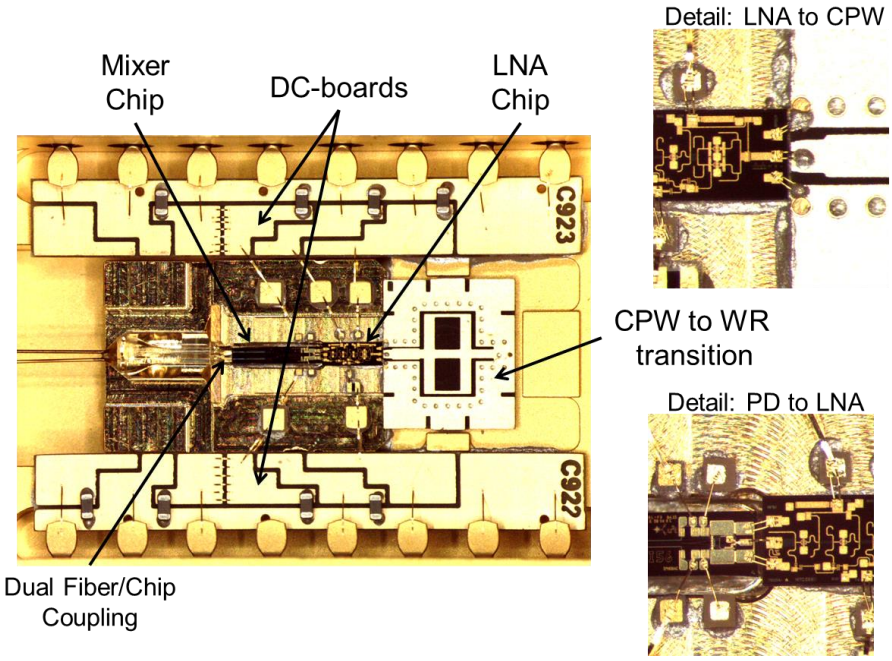


Figure 10: Pictures of the internal layout of the first coherent mixer module with LNA.

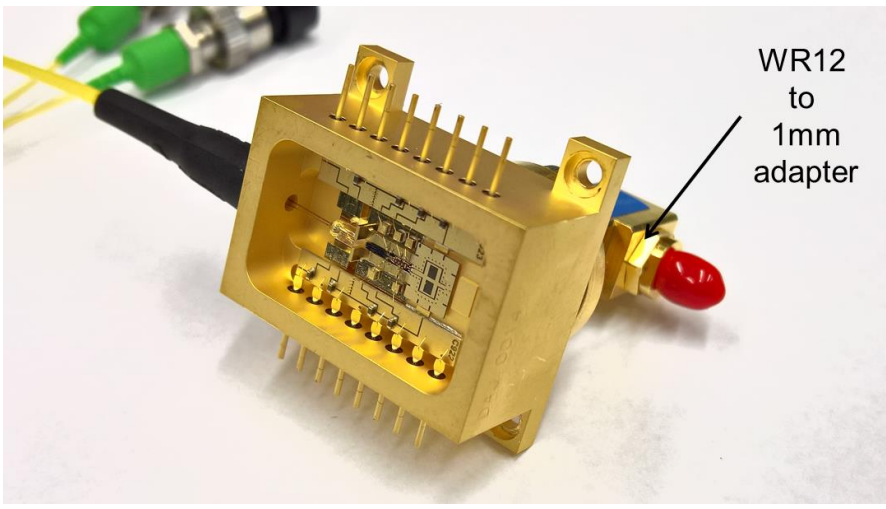


Figure 11: First coherent mixer module with LNA.

For the characterization of the coherent mixer modules as well as the combination from mixer module and electrical amplifier an optimized heterodyne setup was previously developed. Details of the new measurement system were reported in Section 4.1 of deliverable D421.

Altogether three modules were assembled and characterized on module level. The responsivity is 0.20 A/W @ 1550nm and >0.15 A/W over the entire C-band, PDL is <0.5 dB. Due to the WR output of the module the overall RF-response is a convolution of the mixer chip and LNA response, CPW to WR12 transition and the characteristic of the WR12 transmission. The mixer chip on the one hand is a broadband device (DC to 100 GHz), whereas the LNA and the transition as well as the WR12 waveguide have only a limited pass band in the E-band.

The RF output power version optical input power for a 100% modulated heterodyne signal @ 73 77.5 and 83 GHz is shown in Figure 12. The highest RF-output power is achieved at around 78 GHz with values of 14 dBm.

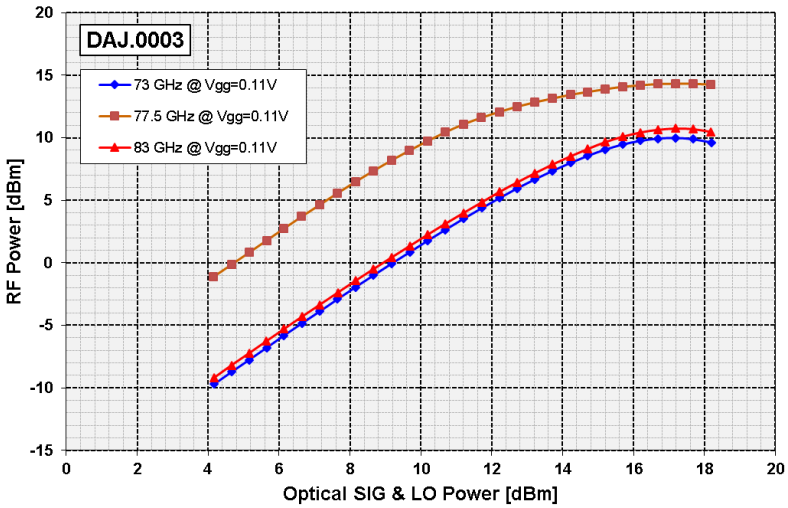


Figure 12: RF output power of a coherent mixer module vs. optical input power of a heterodyne signal at 73, 77.5 and 83 GHz.

Because of the limited availability of the modules, we (FINISAR) didn't want to risk too much before using the modules in first system tests (LNA mixer module from FINISAR plus high-power amplifier from SILKU) at UDE. The measured RF output power versus optical signal power is shown in Figure 13. The targeted output power of >17dBm was clearly achieved.

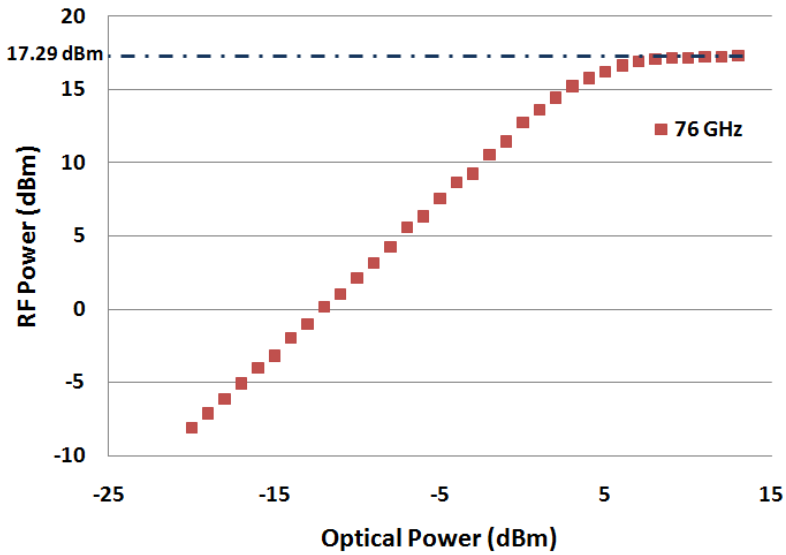


Figure 13: RF output power versus optical signal input power from LD1 for a detector chain containing a coherent mixer module (FINISAR) and RF amplifier module (SIKLU).

If one compares Figure 13 with Figure 12, one can clearly identify the impact off Siklu's HPA. In summary, we reported on the development of first E-band photoreceiver modules with mixer chips and low-noise electrical amplifiers (LNAs). The optical receiver characterization revealed that this module alone already provides an RF output power of 14dBm @ 78GHz. If one now measures the RF output power versus frequency, one gets the following results. The output power is in a broad

range (72 to 84 GHz) above 14 dBm and therefore more than enough for the targeted 10 dBm output power at the antenna.

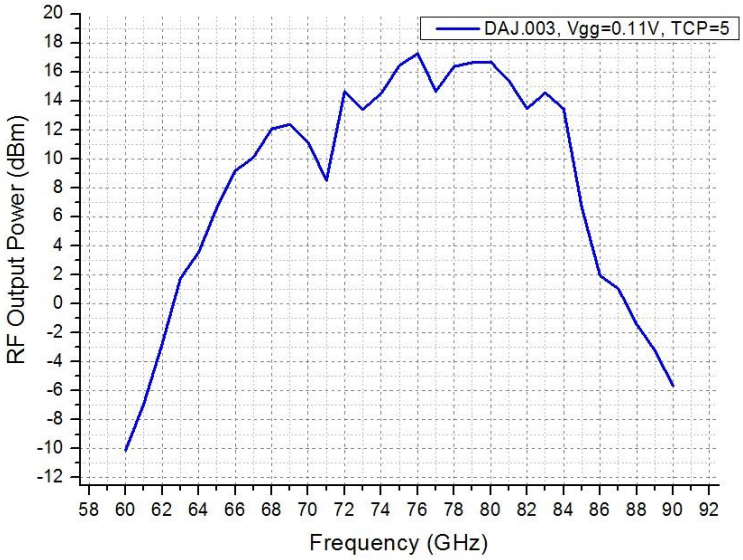


Figure 14: RF output power versus RF frequency.

RF modulator package led by AXENIC

The work focused on the development of packaging for the SSB modulator. It was found that the modulator performance is highly conditioned by its packaging. As originally conceived, the preferred RF interface for an E-band modulator would be based on WR12 rectangular waveguide, possibly set into the base of the package (see Figure 15).

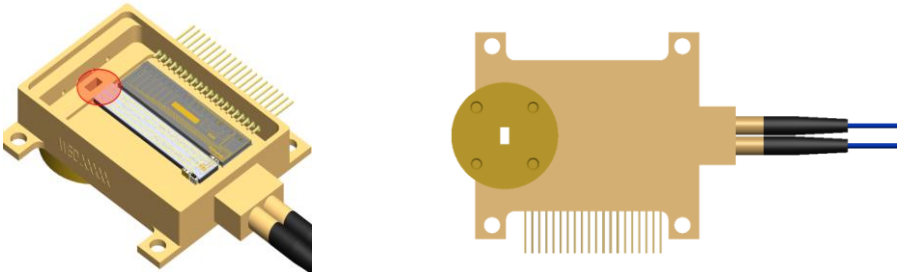


Figure 15: Original WR12 package concept.

Despite promising modelled characteristics for a WR12 transition, such a direct waveguide transition poses significant practical difficulties for a first design.

Hybrid RAU integration (led by SIKLU in cooperation with UDE)

For the seamless integration in WDM-NGOA and legacy GPON networks, hybrid integrated RAUs based upon a novel coherent optical heterodyne detection scheme and frequency-agile low-linewidth lasers serving as photonic LOs in the RAU were proposed. Due to the delay in laser and modulator fabrication at III/V lab and AXENIC, respectively, UDE had developed a USB controllable frequency-agile laser using a commercial product. This laser has been used instead of the low-linewidth laser from III/V lab for first measurements. The laser provides up to +16 dBm output power with a linewidth below 300 kHz and can be adjusted over the full C-band. In addition, UDE

has acquired a 110 GHz polymer Mach-Zehnder modulator from BrPhotonics to replace the AXENIC modulator for the first tests (see D441 for technical details). First tests using the implemented WDM-RAU were performed and direct optic-to-RF and RF-to-optic conversion was successfully achieved within the frequency band of interest between 71-76 GHz (see D441). Figure 16 shows the architecture of a hybrid integrated IPHOBAC-NG RAU for seamless integration in WDM PON using the frequency-agile UDE lasers, the BrPhotonics MZM, and the coherent photonic mixer CPX developed by UDE and FINISAR (see D421 for CPX details).

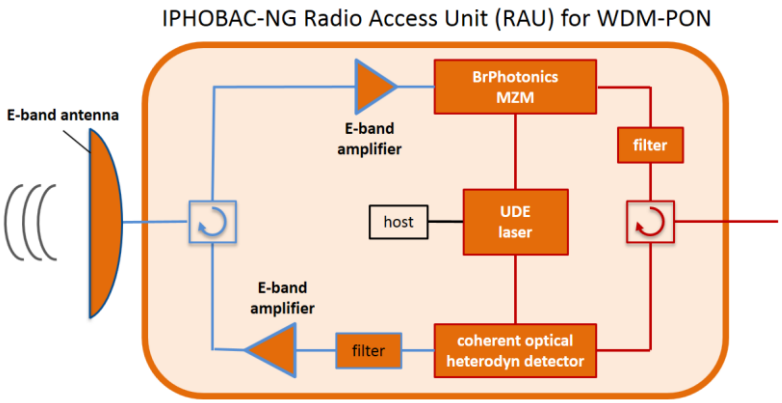


Figure 16: Hybrid RAU architecture for WDM-PON using UDE lasers, BrPhotonics MZM and the UDE/FINISAR CPX.

In order to create a wireless bridge between for a WDM-PON fiber infrastructure, two RAUs (one RAU at the central office site and another one at the customer site) are necessary. For downlink transmission, the optical WDM channel is direct optic-to-RF converted using the CPX. Here, the wavelength difference between the LO laser from UDE and the optical WDM input channel is the wireless carrier frequency. After wireless transmission, the received RF signal is RF-to-optic converted using the BrPhotonics modulator. The proposed system architecture to experimentally study such a hybrid fiber wireless link is shown in Figure 17.

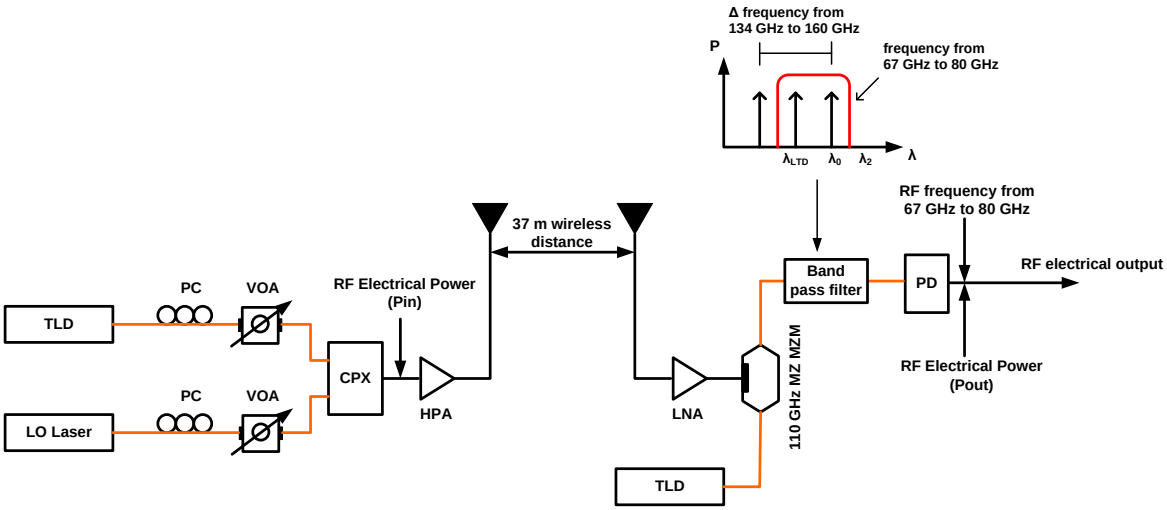


Figure 17: 100 Gbit/s MZM in the coherent radio over fiber system with a 37 m wireless distance link (67-80 GHz), including signal laser (TLD), optical LO laser (LO), variable optical attenuator (VOA), high power amplifier (HPA), low noise amplifier (LNA) and photodiode (PD).

In addition to the WDM-RAU, D441 also described the development of a hybrid GPON-RAU that is needed for the IPHOBAC-NG field trial, which aims at implementing the IPHOBAC-NG RAU in a real-world GPON system operated by ORANGE in Poland. Therefore, in D441, a modified concept was proposed. The IPHOBAC-NG RAU for GPON wireless extension concept is based upon the coherent radio-over-fiber (CRoF) approach, aiming at employing coherent heterodyne optical detection in the RAU for the generation of the wireless signal without phase-locking of the two lasers. This is a great advantage in terms of complexity and cost but leads to a non-stable RF carrier frequency. Therefore, the use of an envelope detector as wireless receiver instead of a heterodyne receiver was proposed in D441. The architectural concept for a hybrid RAU for GPON as introduced in D441 is shown in Figure 18.

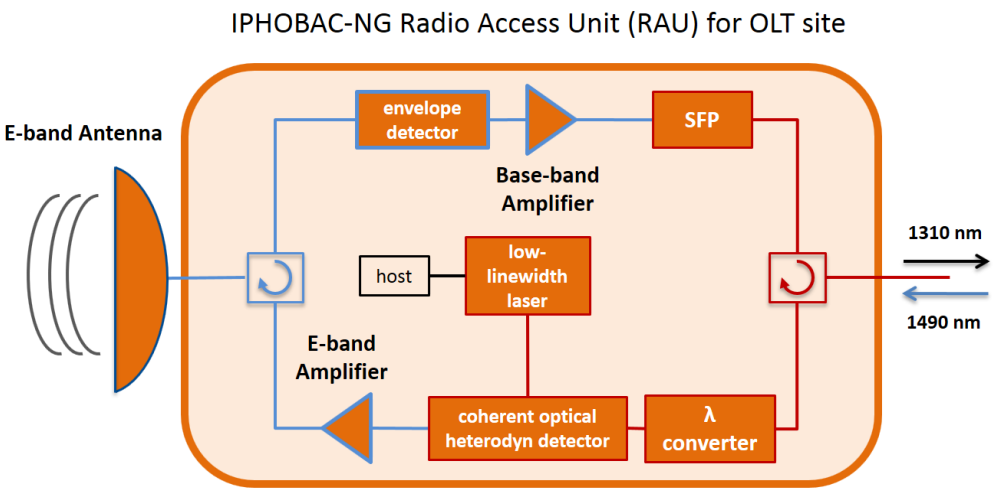


Figure 18: RAU architecture using a CRoF approach for GPON.

The hybrid RAU includes the amplification modules which connect the RF-to-optical and optical-to-RF conversion modules with the antenna through an optional duplexing device. The entire chain purpose is to provide the required gain and RF signal power that will enable the RF-to-optical conversion modules to function properly, and maximize the distance achievable by the link. The entire sub-system is targeted to have a low-cost and support a large dynamic range to enable both short and long links with optimal driving level for the conversion modules. The IPHOBAC-NG RAU block diagram is depicted below.

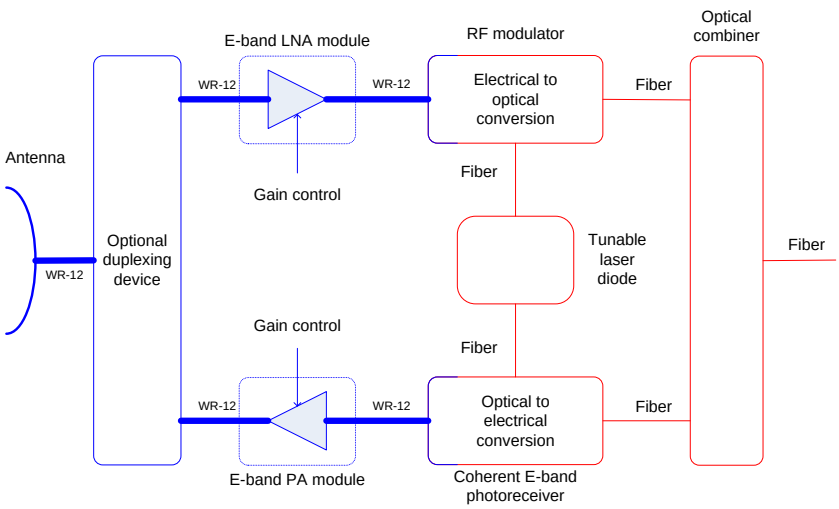


Figure 19: Hybrid RAU block diagram.

Integration activities have started with integrating together the RF sub-system parts. The amplifier modules (PA and LNA) where connected together and integrated with the E-band antenna, which has been characterised as well (shown below).

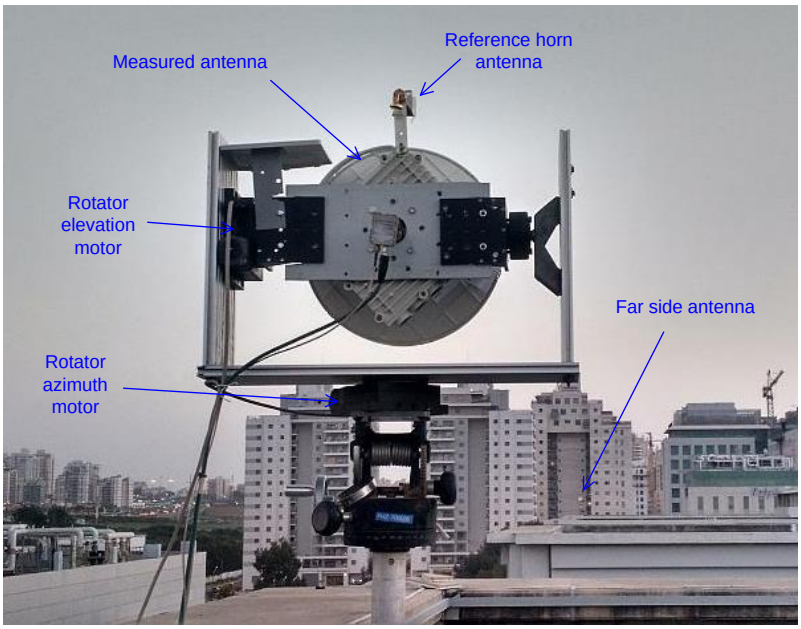


Figure 20: Antenna on measurement setup.

The integration concept enables either use of the Full E-band (70/80GHz) with use of a diplexer component, or use of just half the band (70GHz only) with relying on the inherent isolation between the antennas to facilitate full duplex operation.
A full one way testing of the RF path, including amplifiers and antennas over the air was done to ensure that the RF sub-system is ready for integration with the optical components (shown below).

Figure 21: Full one way test setup of RF sub-system.

The RF sub-system integration activity has been reported in deliverable D442, and has met the specifications required in order to be successfully integrated with the optical part of the RAU. For Hybrid Fiber Wireless (HFW) experiments with the hybrid RAU, the antennas and the amplifiers were delivered to UDE.

D433 reported on long-distance wireless test comparing the CPX (see D421 and 422 for details) for direct optic-to-RF conversion. An SBD that was already described in D441 was used as wireless receiver in both cases. When using a pseudorandom bit generator for the data modulation, we achieved error-free 40 m wireless transmission (BER< 10^{-9}). The receiver sensitivity for 1.0 Gbit/s and 2.5 Gbit/s OOK signals was measured to be -43 dBm and -39 dBm, respectively. The corresponding transmitted RF power levels were -29 dBm and -25 dBm, respectively. Figure 22 shows the BER versus the received RF power for 1.0 Gbit/s and 2.5 Gbit/s (NRZ-OOK) data rates.

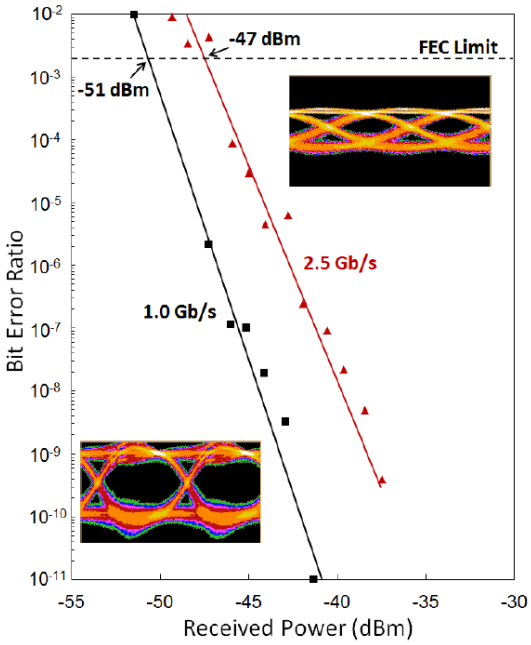


Figure 22: Bit error ratio over received power for 1.0 Gbit/s (squares) and 2.5 Gbit/s (triangles), respectively. Eye diagram of error-free operation for 1.0 Gbit/s (bottom left) and 2.5 Gbit/s (top right), respectively.

Even when using a real-time 1 Gbit/s HDMI signal with a somewhat lower quality, i.e. a smaller SNR, an error-free wireless transmission was successfully achieved and reported in D443. Field trials were carried out at different wireless distances of 92 m and 230 m between the RAU and the wireless receiver. Here, the 92 m backhaul link has been established on the campus, while the 230 m field trial has been carried out on a suburban farm, as shown in Figure 23. When transmitting a real-time 1 Gbit/s HDMI video signal data at 76 GHz over 92 m and 230 m using the IPHOBAC-NG CPX, the wireless receiver sensitivity were as low as -34.8 dBm. The transmit power levels for 92 m and 230 m wireless transmission were -11.17 dBm and -3.36 dBm, respectively. Some aberrations are present in the eye diagram, especially an overshoot can be observed. This can be traced back to the high-power amplifier stage in the transmitter amplifier chain. Note that the overshoot was not present in eye measurements at shorter wireless distances of 40 m that were carried out without the high power amplifier stage.

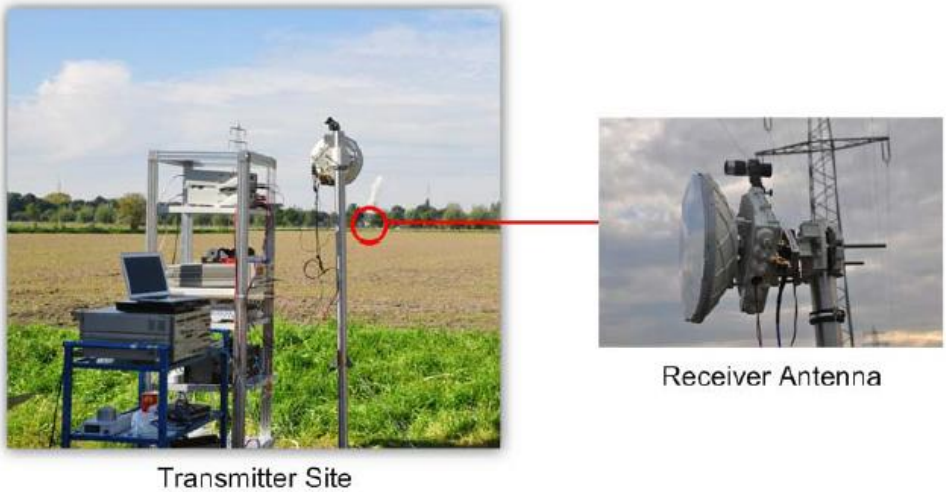


Figure 23: Photos of the constructed wireless transmitter and receiver units used for the outdoor field trials.

Given that the IPHOBAC-NG HPA can provide up to >+17 dBm output power, it is clear that even a real-life 1 Gbit/s HDMI signal (with a reduced SNR as compared to the BRBS signal) can be easily transmitted over large wireless distance using the IPHOABC-NG CPX and HPA. Considering the 230 m experiment, one can conclude that the transmit power level can be further increased by about 20 dB. This corresponds to an 8 fold longer wireless distance, i.e. 230 m time 8, i.e. approx. 2 km. Figure 24 shows the required transmit power with respect to the wireless distance for an actual CRoF system under investigation.

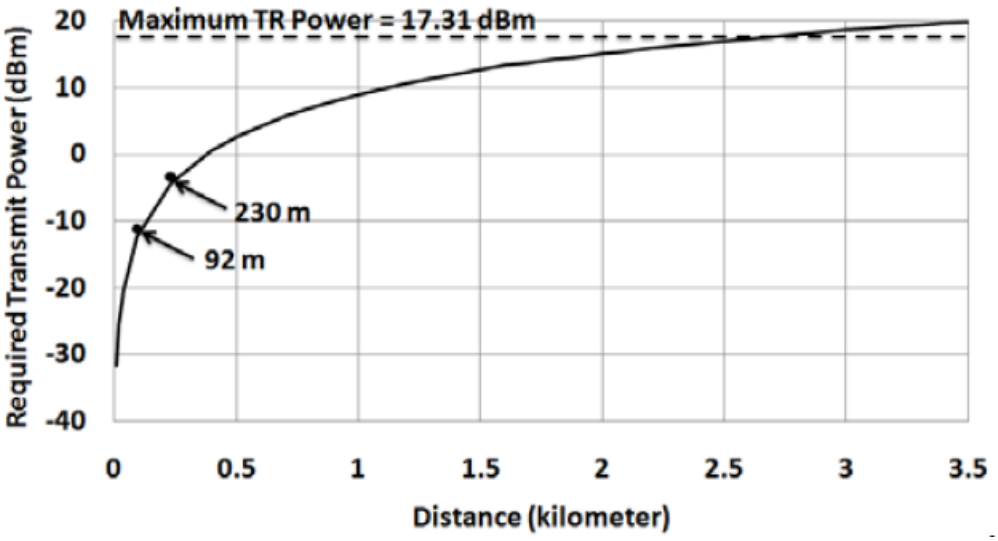


Figure 24: Theoretically calculated transmit power level for achieving a BER=10^{-3} with respect to wireless distance. The experimentally determined transmit power levels for 92 m and 230 m are also indicated.

In summary, the long-distance measurements provide clear evidence, that the IPHOBAC-NG technology will support a wireless extension of a 2.5 Gbit/s GPON signal up to about 2 km

Table 2 Table of main technological project innovations (WP4), as well as expected and achieved outcomes.

Photonic components and sub-system performances (WP4)		
High output-power integrated coherent heterodyne photoreceiver module	Targeted performance specification	Achieved performance specification
Optical wavelength:	1.5 µm	1.31 µm – 1.55 µm
Output power of photoreceiver:	> 15 dBm	> 17 dBm
Photodiode bandwidth:	5 GHz (71-76 GHz and 81-86 GHz)	65 GHz – 85 GHz
Rectangular waveguide integrated photoreceiver for analog applications	Targeted performance specification	Achieved performance specification
Rectangular waveguide:	WR12 (smaller WR possible)	V module fabricated WR12 module fabricated[1]
Integrated amplifier stages:	SiGe or GaAs HEMT	GaAs HEMT in WR12 module
Integrated bias-T:	RF-laminate integration	Two options developed: On-chip MIM Bias-T (FINISAR) ROGERS Bias-T (UDE)
High-frequency:	71-76 / 81-86 GHz and possibly higher	DC – 90 GHz for V-module 65 GHz- 85 GHz for WR12-module[2]
SSB MZM Packaging	Targeted performance specification	Achieved performance
Optical wavelength:	1550 nm	1520 – 1580 nm
Insertion loss:	< 10 dB	Typ. 10 dB at 1550nm 8.5dB at 1520nm
Operating frequency:	70-80 GHz	> 67 GHz. (See 3.3 and 4.3)
RF Vπ:	< 10 V at band center	<7.5 V at 65 GHz
RF Connectors:	G3PO coaxial	GPPO readily upgradeable to G3PO
RF Power requirement	Up to 24dBm x2	Power Amplifier chips by SIKLU. Alternative COTS PA identified from MACOM
PA module	Targeted performance specification	Achieved performance specification
Operation band	71-76 GHz	71-76 GHz
Temperature range	-40 – 85 Cº	-40 – 85 Cº
Gain	45 dB	>50 dB
Gain control	30 dB	>30dB
P_{SAT}	17 dBm	16.9 dBm
LNA module	Targeted performance specification	Achieved performance specification
Operation band	71-76 GHz	71-76 GHz
Temperature range	-40 – 85 Cº	-40 – 85 Cº
Gain	60 dB	>55 dB
Gain control	50 dB	>30dB
NF	8 dB	8 dB

[1] Technology can be exploited for smaller WG down to WR10 (110 GHz). For higher frequencies, i.e. smaller waveguides than WR10, a different sub-mount material is needed because of the limitation in the minimum via hole diameter.
[2] The cut-off of the fabricated WR12 module exceeds the original targeted bandwidth and is mainly defined by the integrated ROGERS transition.

RAU validation in an optical WDM network (led by UCL)

The existing 120 GHz photonic heterodyne signal generator was used to assess the performance and feasibility of implementing a photonic integrated circuit into the RAU. The photonic chip used in this demonstration had two DFB lasers, although only one of them was used as a local oscillator. The other laser was biased below the threshold current to reduce waveguide propagation loss of the incoming WDM signal, which was guided on the chip and coupled to the integrated broad bandwidth photodiode.

The incoming signal and optical local oscillator were heterodyned on the UTC-PD resulting in mm-wave signal, which was then transmitted wirelessly to the receiver antenna. The transmission air link was limited to 4m, due to the size of the laboratory room, by attenuating the received signal by 15 dB. This transmission distance could be increased to over 24 m if the attenuation was removed. The electrical spectrum of 60 GHz carrier and 16-QAM-OFDM data occupying 380 MHz bandwidth are presented in Figure 25 (a). At the receiver, an envelope detector was used followed an oscilloscope to capture the data. To evaluate the performance of the wireless transmission link, the received signal was plotted as a constellation diagram presented in Figure 25 (b). The received wireless 16-QAM-OFDM was characterised to have a SNR better than 20 dB and the average frame EVM RMS was -21.43 dB.

The successful wireless bridge was created allowing for 1.2 Gb/s downlink transmission with a spectral efficiency as high as 3 bits/s/Hz and BER of 1.27 10^{-4}, as described in more detail in D521 report. The use of the monolithically integrated photonic components in RAU offers a clear advantage in terms of an overall size and packaging of the unit, as well as allows for frequency agility of the wireless signal due to tunability of the optical local oscillator.

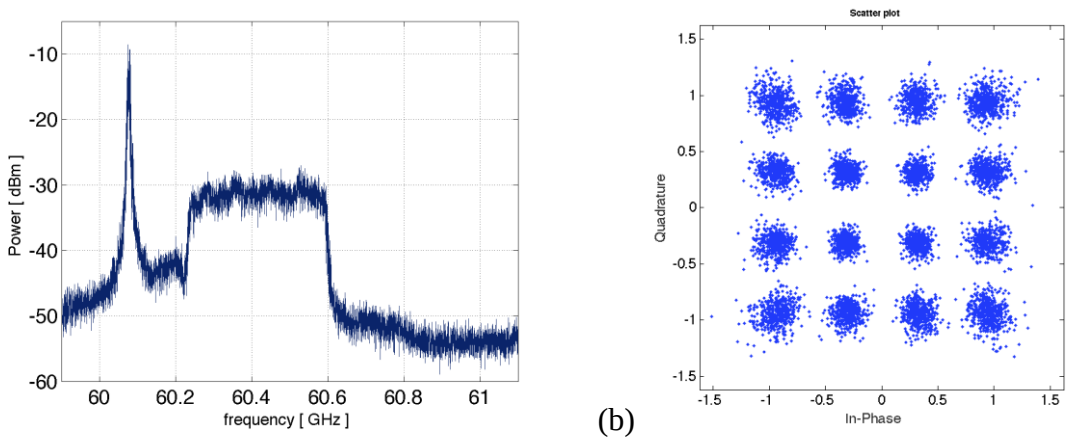


Figure 25: Electrical spectrum of the 60 GHz carrier and OFDM data a) and 16-QAM-OFDM constellation b) measured at the receiver after 100 m on fibre and 4 m wireless transmission.

1-10 Gb/s Photonic RAU in UD-WDM PON Demonstration (led by UDE)

As reported in D531, three major objectives were targeted in task 5.3:

- The implementation of the hybrid IPHOBAC-NG RAU in a lab-based ultra-dense WDM-PON architecture to experimentally study inter-channel interference penalties.

- The implementation of the hybrid IPHOBAC-NG RAU in a lab-based trial using complex modulated optical signals to experimentally study the maximum achievable spectral efficiency and data rate.
- The implementation of the hybrid IPHOBAC-NG RAU in a lab-based GPON infrastructure to experimentally study synchronization between the OLT and ONU as well as maximum wireless extension.

By implementing the hybrid RAU in an ultra-dense optical WDM network, it was shown that the hybrid RAU with the CPX and frequency-agile lasers is suitable for real dense-WDM networks. For 1 Gbit/s PRBS31 double-sideband modulated optical UD-WDM signals, no penalties were observed for optical channel separations as small as 15 GHz. In order to investigate the impact of optical channel spacing of a WDM-PON, BER measurements had been carried out, based on the system setup depicted in Figure 26 (see D531 for details). In the experiments, the median channel was used for data transmission and bit error rate (BER) measurements using a 1 Gb/s pseudorandom binary sequence (PRBS) data signal with a word length of 2^{31} - 1 generated by a pulse pattern generator (PPG). The modulation format was NRZ-OOK.

At the RAU a tunable LO laser was added to the incoming WDM channels by a 3 dB optical coupler whose output was fed to a PD. The polarization state of the LO laser was controlled to be the same as the incoming channels' to optimize the coherent detection. The PD generated the RF signals out of the three channels by heterodyning with the LO signal for direct optic-to-RF conversion of the optical baseband signal. All generated RF channels were amplified by an E-band (60-90 GHz) rectangular waveguide (WR12) based low-noise amplifier (LNA) (see D442 for details), thereby extinguishing all low frequency components arriving at the WR12 input and filtering out the RF channels outside of the LNAs' gain characteristic. The amplified signals were then radiated by a 1-ft cassegrain antenna, designed for the 71-76 GHz band, with a directivity of 43 dBi.

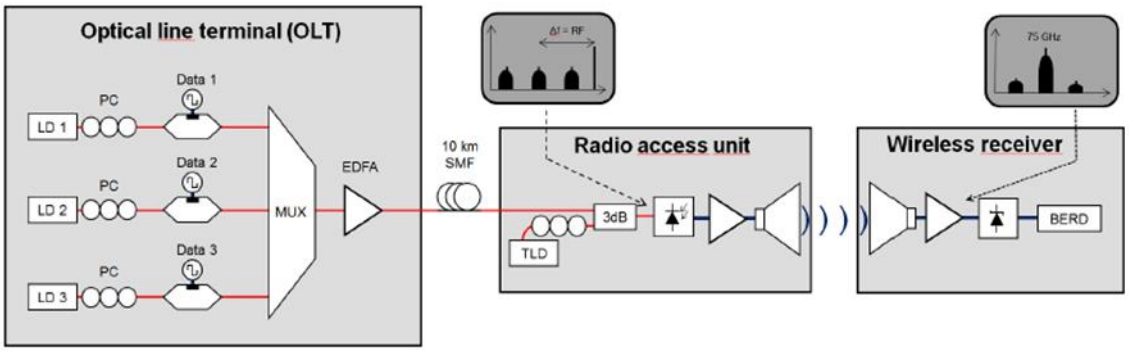


Figure 26: System setup of the WDM-PON architecture for testing the hybrid RAUs.

For the wireless receiver, an antenna of the same type was used. The wireless transmission distance was fixed at 40 m. In the receiver, the signals are amplified using an E-band LNA before being fed to a zero-biased SBD for RF-to-baseband detection.
To study the impact of adjacent channels on the BER performance of the system, the fiber between the OLT and the RAU was increased up to 25 km.

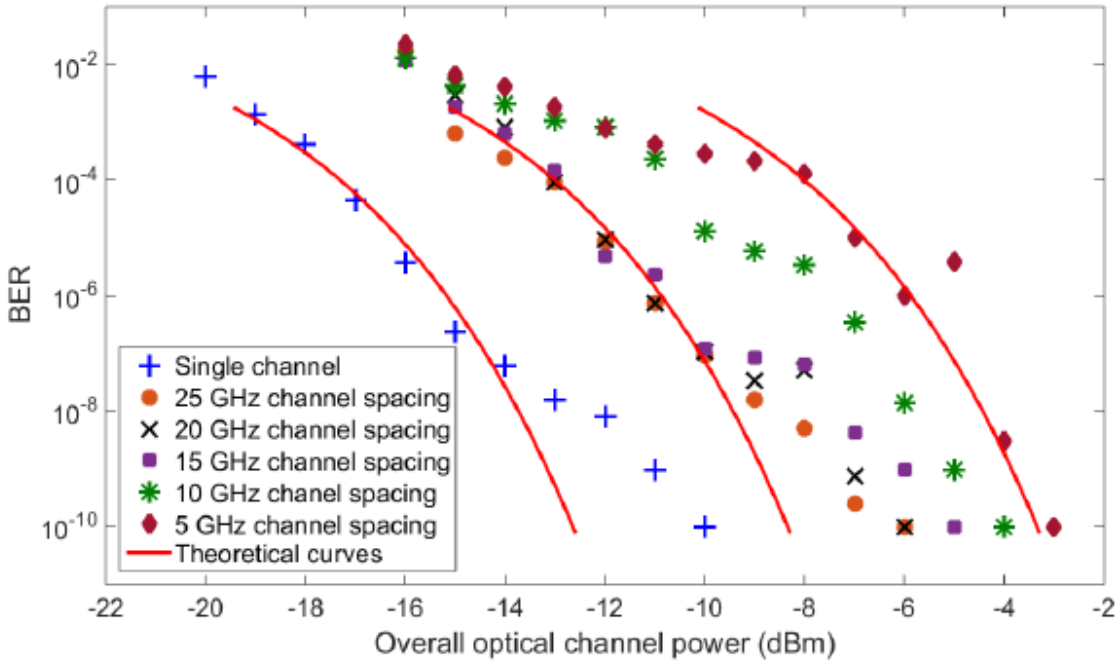


Figure 27: BER measurements over total optical power of all channels before fiber transmission over 25 km.

Figure 27 shows the measured and numerically calculated bit error rate (BER) for different conditions. The signal data rate was 1 Gbit/s using a 2^{31}-1 PRBS signal. The measured BER corresponded well to the theoretically expected behavior for a BER>10^{-7}. For lower BERs, one could observe deviations from the expected behavior, which were unfortunately due to a malfunctioning of the bit error rate tester. For signal channel spacings down to only 15 GHz, no significant penalty was measured. Only for smaller signal channel spacings of 10 GHz and 5 GHz, a penalty of 2 dB and 5 dB, respectively, was observed. This proved that the CRoF approach using frequency-agile lasers for direct optic-to-RF conversion is suitable for WDM systems and for a 1 Gbit/s PRBS31 double-sideband signal, no penalties could be observed for channel separations down to 15 GHz.

For QAM-OFDM modulated optical links, it was shown that the IPHOBAC-NG technology supports record spectral efficiencies up to 10 bit/s/Hz. To our knowledge, this was the highest spectral efficiency achieved for E-band wireless links. The maximum wireless data rate was achieved for 64QAM-OFDM modulated signals. If one exploited the full 7 GHz bandwidth of the 57-64 GHz band, the maximum achievable wireless data rate was 42 Gbit/s. This was clearly outperforming the original IPHOBAC-NG target to demonstrate wireless transmission of 10 Gbit/s signals.
Figure 28 shows the experimental setup of the hybrid RAU (D531). The principles of the direct optic-to-RF and RF-to-baseband schemes were further introduced in D531. The CPX, which was employed for direct optic-to-RF conversion, was already reported in D422. The balanced detection arrangement in the CPX yielded high power in the 60 GHz band and suppressed the noise. Envelope detection using a zero-biased Schottky barrier diode reduces optical phase noise and no optical phase lock-loop or phase tracking between the two lasers was necessary (see D441 for details).

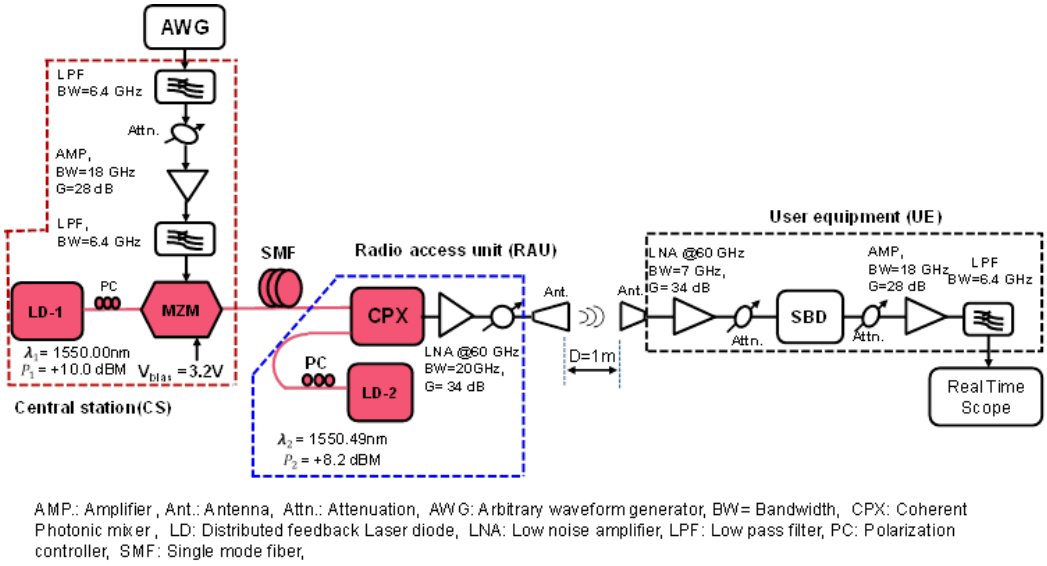


Figure 28: Experimental set-up using the hybrid RAU for QAM-OFDM modulated optical carrier.

For achieving a high spectral efficiency of 9 bits/s/Hz in the system, an OFDM signal bandwidth of 1GHz with an appropriate IF carrier frequency of 1.75 GHz was used. Figure 29 shows the received 512-QAM constellation, received IF signal spectrum and received SNR per subcarrier respectively. In the experiment, the following OFDM system parameters were used: IFFT / FFT size: 1024, Cyclic Prefix: 7%, Training Frames: 5, Data Frames: 300, AWG / Real-time scope sampling rate: 12.5 GHz. As shown in Figure 29, an error-free of wireless transmission of 8.79 Gbps was experimentally demonstrated with an SNR = 25.80 dB, EVM = 5.13 % and (BER<1E-6) for a transmitted RF power of -2.79 dBm. For BTB case, an SNR = 27.45 dB and EVM = 4.24 % were achieved.

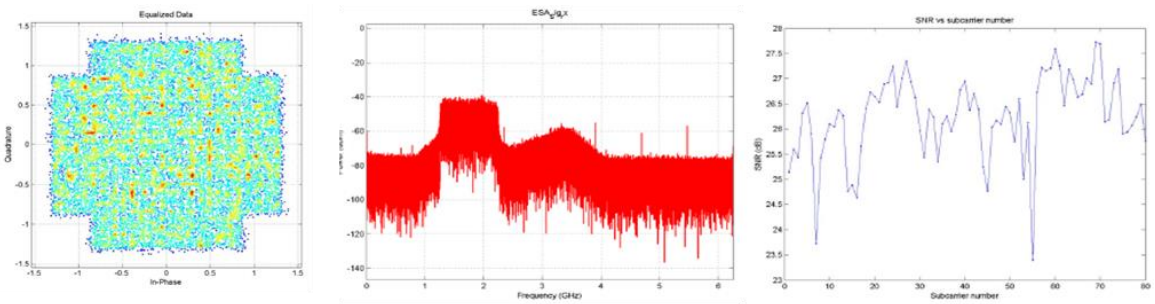


Figure 29: Constellations (left), spectra (middle), and SNR per subcarrier (right) of the down-converted 512-QAM-OFDM 8.8 Gbit/s signal.

To achieve a higher throughput, the bandwidth of the signal was increased from 1 GHz to 3.5 GHz and a lower modulation format of 64-QAM instead of 512-QAM was used to account the reduced SNR. The basic OFDM parameters remained same as in the previous measurement except that IF frequency was increased to 2.5 GHz in order to minimize the impact of SSBI coming from the increased signal bandwidth. The performance of wireless transmission of 20.9473 Gbps of the received 64-QAM constellations, with an averaged received SNR = 18.74 dB (BER~1E-6) and EVM = 11.57 % is shown in Figure 30.

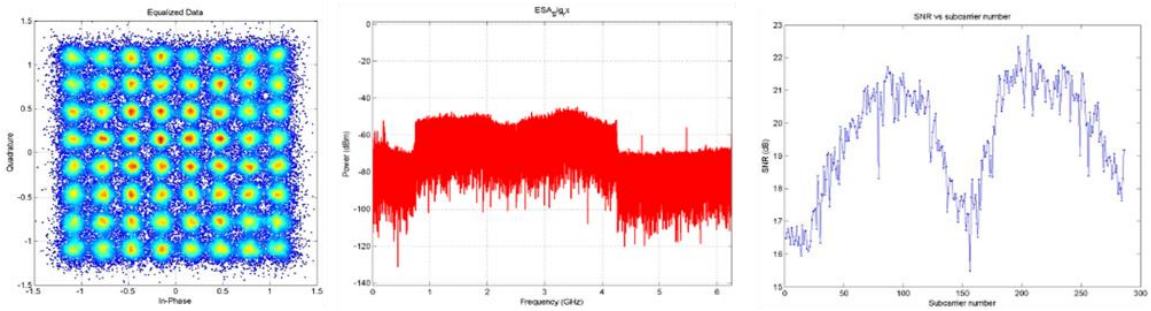


Figure 30: Constellations (left), spectra (middle), and SNR per subcarrier (right) of the down-converted 64-QAM-OFDM 21 Gbit/s signal.

The experiments had proven that the approach and the IPHOBAC-NG CPX transceiver technology are supporting record-figure spectral efficiencies.

Finally, successful synchronization between a commercial OLT and commercial ONU from Huawei was shown using the hybrid IPHOBAC-NG RAU to realize an E-band wireless extension of a GPON network. It was experimentally confirmed that the maximum wireless distance that the hybrid RAU will support is at least 500 m. When using better SFPs, much longer wireless distances were expected. This confirmed the suitability of the hybrid RAU for the planned GPON field trial in Poland.
The architecture of the hybrid RAU for wireless extension of GPON is shown in Figure 31. For uplink transmission between the OLT and the UNU (or ONT) at 1490 nm optical wavelength a λ-converter is used to for transparent 1490 nm to 1550 nm wavelength conversion. The CPX (see D422) and the UDE frequency-agile lasers (see D441) are used for direct optic-to-RF conversion. For the wireless reception, an envelope detector is employed for RF-to-baseband conversion in conjunction with a commercial SFP laser for re-modulating the GPON signal onto the correct wavelength (1490 nm for downlink transmission).

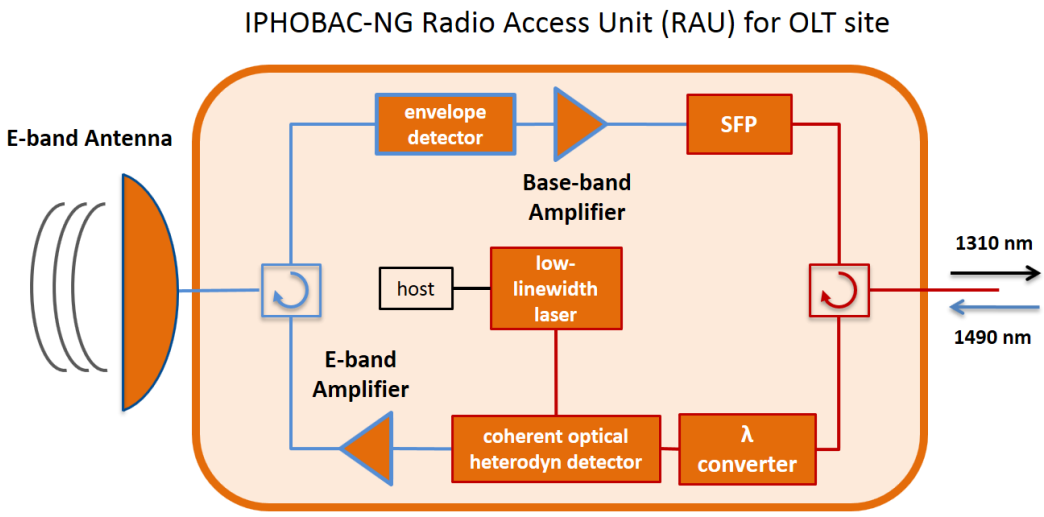


Figure 31: Architecture of the hybrid RAU for GPON wireless extension.

For testing a HFW wireless extension of GPON using the IPHOBAC-NG RAU, an experimental setup as depicted in Figure 32 was used (see D531 for further details).

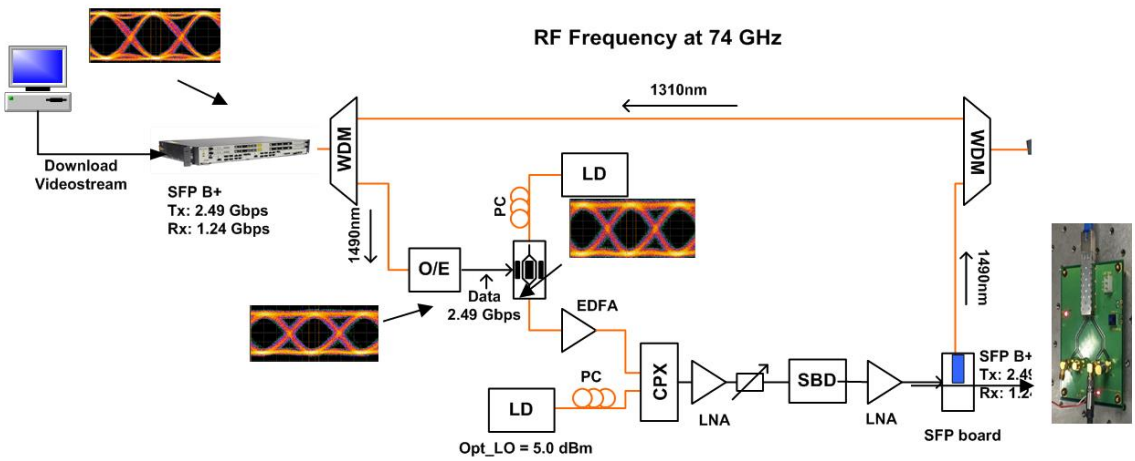


Figure 32: Architecture of the GPON lab test at UDE.

For testing the maximum wireless link distance that the system can accommodate, we measured the minimum and maximum RF power after the RF attenuator, i.e. the received RF power. The minimum power is given by the minimum received power required for successfully synchronization between the OLT and the ONU. The maximum received RF power is given by the maximum safe input power for the SBD which is -12 dBm.

Figure 33 shows the electrical power to the re-modulation unit, i.e. the SFP board versus the received electrical power. Here, the received electrical power was changed using the RF attenuator between -12.72 dBm down to -19.72 dBm. Note that since the SBD was a square-law detector, the baseband power input to the SFP module changes quadratically with the received RF input power, as can be seen from Figure 33.

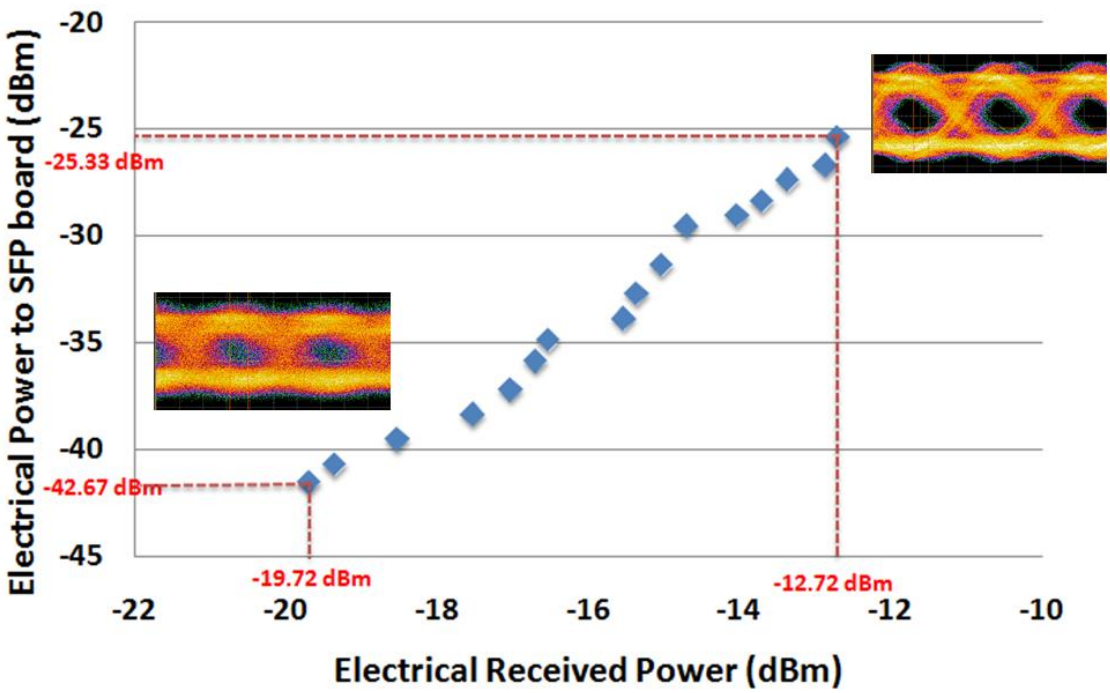


Figure 33: Electrical power to SFP board versus electrical received power in the GPON extension system.

For determine the maximum wireless distance that the system could accommodate, it was necessary to verify the RF attenuation used for the system tests. Since the RF transmit power before the attenuator, i.e. after the CPX and the LNA was fixed at -6 dBm, the RF attenuation was between -6.72 dB and -13.72 dB. Assuming the usage of the 43 dBi SIKLU antennas, this corresponded to wireless distances between 14 m and 32 m at the wireless carrier frequency of 74 GHz. As reported in D422, the transmit power level could be increased up to >+17 dBm using the new CPX and an HPA from SIKLU, i.e. the transmit power could be increased by about 23 dB. Thus, the maximum wireless distance that the system in the current configuration could cover is about 500 m.

Hybrid RAU Implementation in GPON Field Trial (led by ORANGE)

As already reported in the 1st review and D112, the consortium had agreed to conduct the validation of the hybrid RAU in a GPON field trial in Poland led by ORANGE.

In D443, we already proposed the concept for a hybrid RAU based upon the coherent RoF (CRoF) approach and frequency-agile lasers from UDE for the planned GPON field trial in Poland using the real-world GPON infrastructure from ORANGE.

In the D511 report, we then presented the test bed scenarios for the validation of the hybrid RAU developed in IPHOBAC-NG. These tests included RF component level tests, RF related system level tests, and scenarios for PON testbeds. These scenarios were developed to assess the lower and upper boundaries in terms of operability of the RAU.

In the deliverable D531, the hybrid IPHOBAC-NG RAU designed for the field test in Poland were implemented and tested in the UDE laboratory. This report also describes the process of analysis, preparation and initial prototype implementation proposed.

Finally, the RAU field tests have been performed in Garwolin (Poland, 60 km away for Warsaw) in January 2017. Technical details on the field trial are summarized in the D541 report.

The RAU wireless link reflects implementation of the device already described in D531 in Chapter 5: Hybrid RAU implemented in GPON. This RAU had been tested for compatibility with a commercial Huawei OLT, which is used within OPL network of ORANGE. The wireless link distance between two mobile network towers is 455 m and it had the following key parameters:

Receive optical power level of ONTs: -18dBm ±1dB.
RF frequency operating: 74.60 GHz
Transmit power: +4dBm
Receive power: -40.38 dBm
Antenna gain: 43dBi

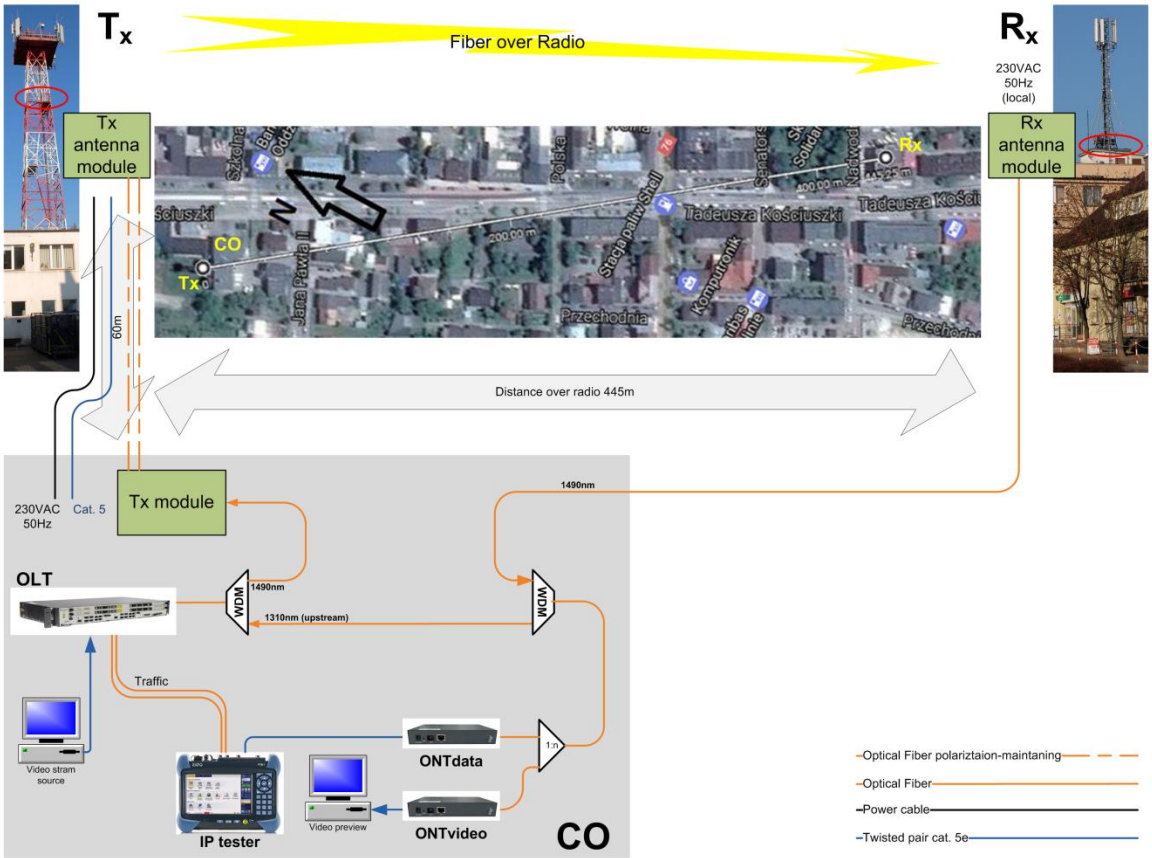


Figure 34 Planed setup – DEMO

Based upon the information form UDE regarding the RAU configuration and requirements for DEMO purposes and based upon the local on-site investigation, a test configuration has been prepared (see Figure *Figure 34*). It covers transmission and tests system installation along with proper system and surrounding infrastructure.

For implementing the hybrid RAU, all the necessary modules were sent from UDE to ORANGE. The hybrid RAUs were then re-constructed in Garwolin by UDE, ORANGE, SIKLU and in collaboration with NEXTEL using rigid boxes to protect the technology from winter weather conditions. The hybrid RAUs utilize the IPHOBAC-NG CPX, and the SIKLU RF amplifiers and antennas as well as the frequency-agile lasers developed by UDE. Details can be found in the D541 report. The RAU operates in the 71-76 GHz band and can transmit power levels in excess of +17 dBm in general. On behalf of ORANGE, NEXTEL supported the IPHOBAC-NG consortium in the housing and mounting of the RAU on the radio towers.

Figure 35: Constructed 71-76 GHz RAU for wireless GPON extension.

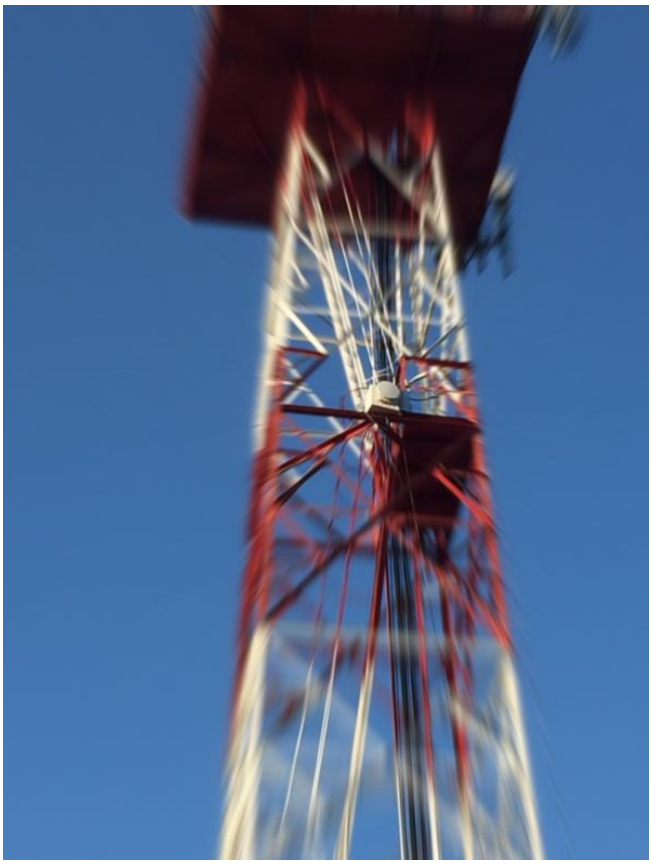


Figure 36: One of the constructed 71-76 GHz RAU mounted on an ORANGE radio tower for testing wireless GPON extension in Garwolin, Poland.

The mounting of the RAUs on the operator's towers was supported by NEXTEL on behalf of ORANGE. Details on the field trial implementation and the previous tests that were carried out a week before the field trial in an ORANGE laboratory in Świdnik are summarized in the D541 report.

ORANGE managed all legal requirements and obligations required by the local regulator regarding the frequency allocations for the tests. Within the test environment, G-PON was synchronized at 2.5 Gbit/s with a traffic load of 2 times 1 Gbit/s and a parallel video channel in the forward path.

During the tests, the quality of the signal was maintained at sufficient level. The obtained results show potential capability to increase throughput values to the level close to the maximum G-PON channel utilization (2.5 Gbit/s). Detailed test reports will be reported during the final review and can be found also in D541.

In summary, the RAU field tests and obtained results allow to conclude that a future commercial photonic RAU would be a very promising solution for building a wireless access network extension.

Table 3 Table of main technological project innovations (WP5), as well as expected and achieved outcomes.

RAU supporting 1-10 Gb/s data-rate per client (WP5)		
Integrated E-band RAU in ultra-dense optical WDM access network	Targeted performance specification	Achieved performance specification
Data rate:	> 1 Gbit/s up to 10 Gbit/s	21 Gbit/s experimentally demonstrated[1]
Wireless span:	> 1 km for 1 Gbit/s > 100 m for 10 Gbit/s	~ 2 km for 2.5 Gbit/s[2] t.b.c.
Optical channel separation	< 50 GHz down to 3 GHz	< 50 GHz down to 5 GHz[3]
Integrated E-band RAU for mobile backhauling in CDWM PON network	Targeted performance specification	Achieved performance specification
Data rate:	> 1 Gbit/s up to 3 Gbit/s	2.5 Gbit/s demonstrated in GPON field trial
Wireless span:	2 km for 3 Gbit/s	~ 2 km for 2.5 Gbit/s[2]
Optical channel separation	100 GHz or 400 GHz	CDWM in GPON[4]

[1] 21 Gbit/s were demonstrated for a bandwidth of 3.5 GHz in the 57-64 GHz band. When utilizing the full-bandwidths, maximum data rates of about 40 Gbit/s can be expected. For a 10 GHz bandwidth, a data rate of 60 Gbit/s has been experimentally demonstrated [Optics Express paper submitted].
[2] In the field trail, 2.5 Gbit/s were transmitted over 500 m with a transmit power of 4 dBm. The maximum transmit power is +17 dBm, i.e. for the GPON field-trail wireless distances in excess of 2 km can be expected. Note that the SNR using commercial SFP is limited. A better SFP would allow substantially longer wireless distances.
[3] For a 1 Gbit/s data channel (double sideband modulation), a minimum wavelength channel separation down to 5 GHz has been demonstrate. There is no penalty for wavelength separations down to 15 GHz. For smaller wavelength channel separations, a penalty between 2-4 dB is observed. An adaptive spectral filter or electrical SSB would further improve this.
[4] Channel separation in GPON is 1490 nm for downlink and 1310 for uplink transmission.

Project's potential impact and dissemination

Impact on white papers and standardization

- "Applications and use cases of millimetre wave transmission", white paper
- "V-band street level interference analysis", white paper
- Analysis of antennas for millimetre wave transmission", white paper
- ISG mWT View on V-band and E-band Regulations
- "mmWave Semiconductor Industry Technologies", ETSI White paper
- IEC 103/122/CDV "Safety requirements for radio transmitting equipment" and its translation to DIN EN 60215
- IEC 103/120/CDV "Measurement Method of a Frequency Response of Optical-to-Electric Conversion Device in High-Frequency Radio on Fiber Systems" and its translation to DIN EN 62801
- IEC 103/112/CV (DIN EN 802) "Measurement Method of a Half-Wavelength Voltage and a Chirp Parameter for Mach-Zehnder Optical Modulator in High-Frequency Radio on Fibre (RoF) Systems".
- IEC 103/126/CDV (DIN EN 803) "Measurement Method of a Frequency Response of Optical-to-Electric Conversion Device in High-Frequency Radio on Fiber Systems". This standardization document details and defines ways to characterize and standardize high-frequency o/e-converters in RoF systems.

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[41] K. Balakier, M. P. Thakur, F. Van Dijk, M. Lamponi, M. Chtioui, Y. Leiba, J. E. Mitchell, A. J. Seeds, and C. C. Renaud, Demonstration of Photonic Integrated RAU for Millimetre-wave Gigabit Wireless Transmission, International Meeting on Microwave Photonics, MWP 2016, Long Beach, CA, USA, 31 Oct - 03 Nov, pp. 344–347, 2016

[42] A. Stoehr, V. Rymanov, B. Khani, Y. Hu and M. Hofmann, Applications for Optical Components in THz Systems, IEEE/OSA Optical Fiber Communications Conference (OFC), Los Angeles, March 19-23, 2017 (invited)

[43] Chorchos, Ł, Rommel, S, Turkiewicz, JP, Tafur Monroy, I & Vegas Olmos, JJ 2016, 'Remote Access Unit for Optic-to-Wireless Conversion' Progress In Electromagnetics Research Symposium 2016, Shanghai, China, 08/08/2016 - 11/08/2016, DOI: 10.1109/PIERS.2016.7734974

List of press releases

The complete list of all press releases is published on the project's website http://www.iphobac-ng.eu.

WAZ – Der Westen, 02/2015

WAZ, a German newspaper, reported on February 23, 2015 about "University of Duisburg-Essen conducts research on cellular networks inside street lamps". [»more]

WDR – Westdeutscher Rundfunk, 03/2015

WDR, a German TV broadcast station reported on March 3, 2015 about "Cellular networks of the future". [»more]

WAZ – Der Westen, 03/2015

WAZ, a German newspaper, reported on March 19, 2015 about "Future internet will be inside street lamps". [»more]

3sat – Nano, 05/2015

3sat, a German-Austrian-Swiss TV broadcasting station reported on May 27, 2015 within its science magazine "Nano" about future developments in wireless networks. [»more]

Süddeutsche Zeitung, 06/2015

SZ, a German newspaper, reported on June 9, 2015 about the "Revolution of Internet Speed ". [»more]

University of Duisburg-Essen, 11/2015

Rattana Chuenchom, currently enrolled at the University of Duisburg-Essen as PhD Student, has been awarded at the MWP 2015 the prize for the Best Overall Paper for her work entitled "Integrated 110 GHz Coherent Photonic Mixer for CRoF Mobile Backhaul Links". [»more]

RAPID 5G website, 10/2015

UDE has performed mm-wave radio-over-fiber transmission experiments in the rural areas of Duisburg. [»more]

Alumni Newsletter, 12/2016

Alumni Ingenieurwissenschaften at University of Duisburg-Essen published an article about the IPHOBAC-NG exhibition at ECOC 2016.

[»more]

IPHOBCA-NG exhibits at ECOC 2016, 09/2016

From 19th until 21st of September, IPHOBAC-NG exhibited Coherent Radio-over-Fiber (CRoF) systems for next generation optical access and mobile networks.

[»more]

University of Duisburg-Essen, 02/2017

IPHOBAC-NG succeeds in delivering optical 2.5 Gbit/s GPON over the air using its novel direct fiber-to-radio technology.

[»more]

ORANGE Polska and UDE perform field trials for long distance GPON extension

ORANGE Polska and UDE conducted a pilot test of a prototype radio link system for GPON. This technology will allow in a few years to replace fiber by a millimeter-wave radio link capable of transmitting data rates of up to 10 Gb / s. [»more]

University of Duisburg-Essen, 02/2017

IPHOBAC-NG developed a coherent photonic mixer (CPX) for direct conversion of baseband optical signals to E-band radio (71-76 GHz and 81-86 GHz).

[»more]

www.golem.de, 03/2017

An antenna that bridges the last mile almost lossless has been testet at French network operator Orange. The optical signal is brought at a datarate of 1 GBit / s into the household without optoelectronic baseband conversion and further electronic signal processing.

[»more]

NRZ newspaper, 03/2017

The antennas developed by Prof. Dr. Andreas Stöhr and his team at UDE are capable of transmitting data volumes of up to 40 gigabits per second.

[»more]

Informationsdienst Wissenschaft , 03/2017

Surfing the Internet at ultra-high speed - this is what has been enabled by the worldwide fiber network. However, expansion is progressing at a slug speed, also in Germany and especially in the country side. Unfortunately, laying fibers in the ground is time consuming and expensive. But there is hope: a new photonic antenna unit provides the same speed by radio and can be installed in a few days. It has now been successfully tested in the network of a European telecom company. The antenna was developed by the Optoelectronics department at University of Duisburg-Essen (UDE).

[»more]

www.business-panorama.de, 03/2017

Nowadays people often have little time, everything has to be faster, especially the Internet. Glass fiber is considered as the ne plus ultra, but there are also alternatives. At the University of Duisburg-Essen (UDE), researchers are now testing data transmission using high-speed rf links. The advantage of this method is that, in contrast to glass fibers, no underground cables have to be laid.

[»more]

Furthermore, a number of websites in Poland distributed the results from IPHOBAC-NG's field experiments:

1. http://biuroprasowe.orange.pl/blog/kolejne-testy-czyli-tam-gdzie-swiatlowod-jeszcze-nie-siega/
2. http://www.telepolis.pl/wiadomosci/orange-testuje-radiolinie-o-przepustowosci-swiatlowodow,2,3,38241.html

3. http://www.telko.in/orange-testowal-w-garwolinie-radiolinie-dla-systemu-gpon
4. http://www.telix.pl/artykul.php?sid=78332
5. http://www.gsmservice.pl/19243,Orange_testuje_prototyp_radiolinii,news.html
6. http://www.polskaprasa.pl/2246221-Orange-testuje-radiolinie-o-przepustowosci-swiatlowodow.html
7. http://www.tanierozmawianie.com/nowosci/view/138235/orange-testuje-radiolinie-o-przepustowosci-swiatlowodow
8. http://www.operatorzy.pl/news;more=1741044323
9. http://www.x4studio.pl/2017/02/orange-testuje-radiolinie-o-przepustowosci-swiatlowodow-telepolis-pl/

Project partners

The IPHOBAC-NG consortium was comprised of the following partners:

- Universität Duisburg-Essen, Germany
- III-V Lab, France
- Denmark Technical University, Denmark
- Siklu Communications Ltd., Israel
- ORANGE, Poland
- FINISAR, Germany
- AXENIC, United Kingdom
- Univ. College London, United Kingdom

The IPHOBAC-NG consortium consisted of 8 partners. These partners have been very carefully selected, providing highly complementary synergic expertise in the fields of Photonics, Optical Networks and Wireless Networks.

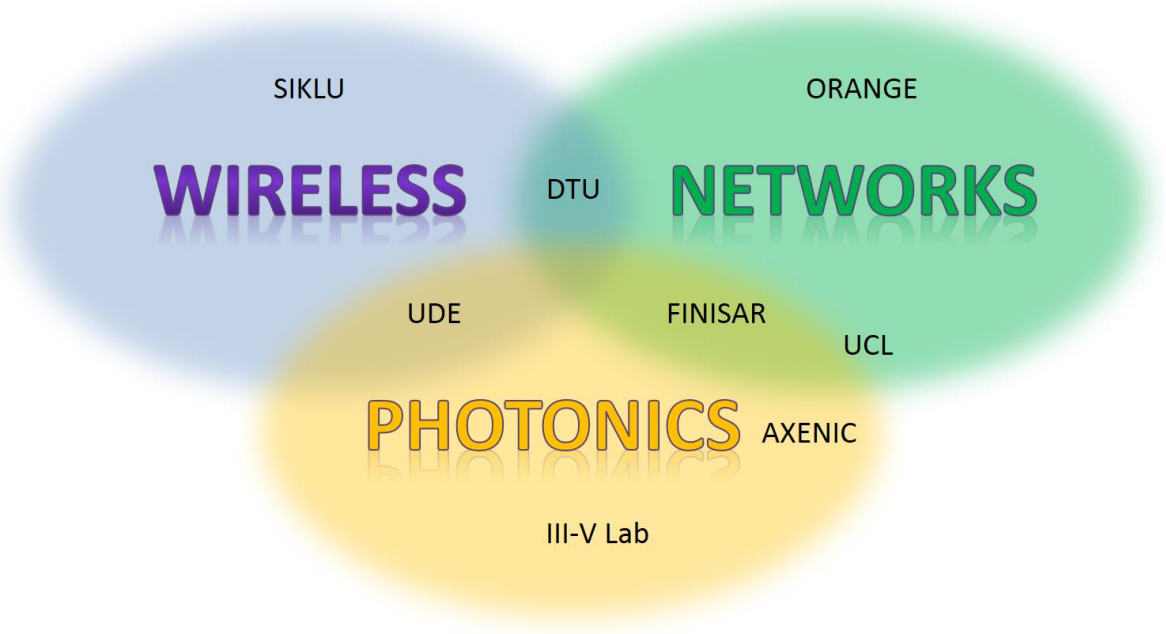

Figure 1: The partner of the IPHOBAC-NG consortium have been carefully selected, for providing long-lasting complementary and synergetic experiences in photonics, networks, and wireless communications.

All IPHOBAC-NG partners were carefully chosen based upon their previous experience and knowledge with respect to their tasks in the project.

In detail, the consortium consisted of a leading European operator (**ORANGE**). In IPHOBAC-NG, ORANGE was responsible for the definition of the GPON field trial and the demonstration of the hybrid RAU in the field trial.

The key wireless experience was brought into the consortium by **Siklu Communication Ltd**. SIKLU is an SME based in Israel and is no. 1 in global millimeter-wave radio deployments with SIKLU's EtherHaul being expected to become a leading technology in millimeter wave wireless backhaul solutions. The company provides award winning carrier-class E-band radio, and is the

perfect partner for providing not only expertise in wireless backhaul solutions but also in development of the E-band amplifier and integration technologies. SIKLU also provided the antennas for the long distance wireless links.

The core of the research activities clearly is in Photonic Component Developments. This is reflected by the constitution of the consortium. Three companies, each of them leading in their respective field, provide the necessary expertise and thus ensure timely exploitation of the project results. For the development of the low-linewidth frequency-agile photonic LO, the French company **III-V Lab** brings in long-years of experience in laser diode fabrication. As regards the coherent heterodyne detection, the German based **FINISAR** company, world leading provider for photoreceiver, is on board. The expertise is completed by the United Kingdom based **AXENIC**, an SME providing years of experience in the fabrication of semiconductor-based high-frequency modulators.

The complementary expertise of the industrial partners is completed by the expertise of three leading universities in the fields of Photonic Components, Radio-over-Fiber, Optical and Wireless Networks. Besides coordination, **University of Duisburg-Essen** (UDE) was mainly active in the development of the coherent heterodyne receiver as well as in hybrid integration of the RAU and system validation. **University College London** (UCL) was mainly responsible for phase locking the photonic LO in the RAU but also supported high-frequency modulator developments and development of test-beds. Last but not least, the **Technical University of Denmark** (DTU) with long years of experience in optical coherent detection will support the activities of the partners mainly in the definition of the laboratory trials but also in modelling and DSP programming.

Project logo, web address and main e-mail contact

Web: www.iphobac-ng.eu

Contact: andreas.stoehr@uni-due.de

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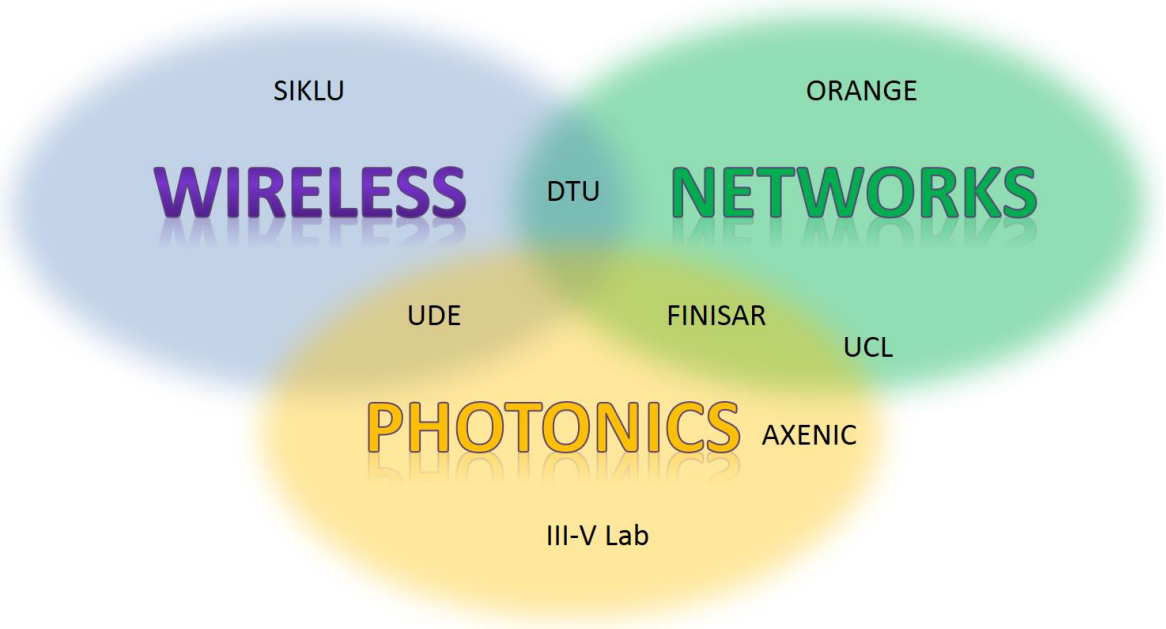

Figure 2: The partner of the IPHOBAC-NG consortium have been carefully selected, for providing long-lasting complementary and synergetic experiences in photonics, networks, and wireless communications.

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