A Converged Copper-Optical-RaDio OFDMA-based Access Network with High Capacity and FlExibility
(ACCORDANCE)

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SEVENTH FRAMEWORK PROGRAMME

FUTURE NETWORKS

European Commission
Information Society and Media

Introduction to the addressed topics

- The demand for modernising available applications to typical residential and business customers in addition to the new breed of service on-the-go customers requires dramatically higher bandwidth network solutions
- Passive optical networks (PONs) based primarily on time division multiplexing (TDM), have evolved as an access solution to provide simplicity and low operational cost with multiple of tens of Mbps provision to each user.
- Wavelength division multiplexed PONs (WDM-PONs) have also been increasingly considered to deliver ultra high-speed services in the critical first mile by enabling service providers to offer dedicated wavelengths straight to homes and businesses over the existing optical backbone.
- Although the escalating demand in bandwidth provision at close subscriber proximity could be widely met by optical networking solutions, next generation access networks should also provide end users with great flexibility and mobility at ease of last-mile implementation.
- The convergence of fixed and mobile networks is likely to deliver all desired benefits of data-centric, quality-service, mobile networks and should be carefully examined and studied.
- This imposes the fundamental challenge of the future access/metro network where transparent integration of wireless and optical servicing at the simultaneous introduction of dynamic multi-wavelength transmission need to be achieved.

Motivation for an OFDMA based access solution

- OFDM: Modulation method for better transmission properties of bit streams
  - Utilizes several low bit rate sub-carriers of the link to carry different QAM symbols simultaneously
- OFDM**A**: Application of OFDM as a scheme allowing for multiple access
  - i.e. different users assigned to different sub-carriers
- OFDM technology currently used in:
  - Copper, in the xDSL links using DMT (Discrete Multi-Tone) modulation format
  - Radio (WiFi:802.11a, 802.11g, WiMax:802.16e-2005, 3GPP LTE)
  - Indoor Power Line Communications (PLC), with the HomePlugAV specifications
- Recently OFDM(A) makes its way into the optics world
  - Core network: Solutions for the optical core network employing OFDM for variable transmission rates from 40 to 400Gbps by dynamically modifying number of sub-carriers (NTT)
  - Access network: A few recent studies show that OFDM can provide high capacity, long-reach and cost-effective operation for Passive Optical Networks (PONs)
  - Use of OFDM in optical access mainly been driven by necessity to increase transmission rates without increasing bandwidth of optoelectronic transceivers, rather than focusing on link optimization
- Convergence of optical infrastructure with wireless solutions also employing OFDM technology seems a beneficial direction to go
  - A few works have appeared which combine wireless and PON technology to limited extent
- No holistic approach has appeared so far for the access, i.e.:
  - One that achieves end-to-end network connectivity addressing the whole layer stack, from the physical and the Medium Access Control (MAC) up to the network layer

State of the art in access networks – EU Research

- In the **PIEMAN** project (ALUD participation) an extended reach PON architecture has been developed that serves 512 users per TDM/TDMA-PON operating at 10G in down- and upstream. Multiple such PONs can be implemented on 32 wavelength pairs (down + upstream) over a 90 km feeder fibre + 10 km drop section. The optical power budget is realised by EDFAs. The DWDM sources are colourless.
  - In the past FP6 project **MUSE**, a similar network has been investigated, however, incorporating an OEO repeater after 70 km having a black&white drop port and a DWDM feeder port, such that no DWDM sources are required at the ONUs.
- In the ongoing FP7 project **SARDANA** (led by UPC), a passive optical ring network serves multiple TDM/TDMA PON trees via WDM. The ring is protected and remotely pumped amplification as well as colourless sources technology is applied. The reach, DWDM channel numbers and bit rates are similar to both PIEMAN and MUSE.
- Another FP7 project (**GigaWAM**) aims at developing component technologies for hybrid TDM/WDM or pure WDM-PONs. In particular new approaches are sought for solving the low cost DWDM-laser issue for application in access networks.
- The FP7 project **ALPHA** investigates architectural and transmission solutions based on the manifold of optical fibres (single-, multi-mode and plastic) as well as wireless technology to support both wired and wireless services in a converged network infrastructure.
- The **FUTON** FP7 project aims at researching, developing and validating a flexible architecture for wireless systems based on the joint processing of the radio signals from distinct remote antenna units and supported by a transparent fibre infrastructure.

About ACCORDANCE

- ACCORDANCE introduces a novel ultra high capacity (even reaching the 100Gbps regime) extended reach optical access network architecture based on OFDMA (Orthogonal Frequency Division Multiple Access) technology/protocols, implemented through the proper mix of state-of-the-art photonics and electronics.
- Such architecture is not only intended to offer improved performance compared to evolving TDMA-PON solutions but also inherently provide the opportunity for convergence between optical, radio and copper-based access.
- ACCORDANCE hence aims to realize the concept of introducing OFDMA-based technology and protocols (Physical and Medium Access Control layer) to provide a variety of desirable characteristics, such as increased aggregate bandwidth and scalability, enhanced resource allocation flexibility, longer reach, lower equipment cost/complexity and lower power consumption, while also supporting multi-wavelength operation.
- In addition, it enables the convergence of the optical infrastructure with standard wireless solutions, thus offering a way to integrate dominant wired and wireless technologies in a hybrid access network supporting seamless ubiquitous broadband services.
- ACCORDANCE is supported by 4 major EU industry partners who will contribute to EU leadership in the particular topics and will support the adoption of ACCORDANCE concepts as global standards.
- The partners strongly believe that the proposed architecture will provide fertile ground for the creation of wider market opportunities from new classes of applications and accelerated uptake of next generation services, by changing the way low-cost ultra-broadband connectivity is provided to end users.

S&T objectives and success criteria - I

- **Definition of a novel Access Network architecture achieving convergence among heterogeneous technologies (optical, wireless, copper).**
  - Clear definition of the ACCORDANCE architecture as a paradigm concept for converged access networks, reported in deliverable D2.1
  - Detailed study of techno-economic aspects for ACCORDANCE, reported in deliverable D2.2
  - Detailed study on how the ACCORDANCE network can interoperate with the rest of the network, reported in deliverable D2.3
  - Detailed technical study on technical issues from the coexistence of wireline and wireless technologies.

- **Propose low-cost, low-complexity concepts to achieve ultra high data rates in the access network (up to 100Gbps aggregate and more than 10Gbps in each segment).**
  - Design of the OLT/ONU transceivers using available components and FPGAs
  - Clearly demonstrate the advantage of OFDM technology over TDM solutions for scaling up to 100 Gbps in the access

- **Introduction of flexible bandwidth allocation concepts using dynamic FDM and OFDM sub-carrier assignment.**
  - Detailed definition of novel MAC protocols for ACCORDANCE
  - Proposal and evaluation via simulations of algorithms taking advantage of the ACCORDANCE MAC
  - Evaluation of the ACCORDANCE MAC on the experimental test-bed

S&T objectives and success criteria - II

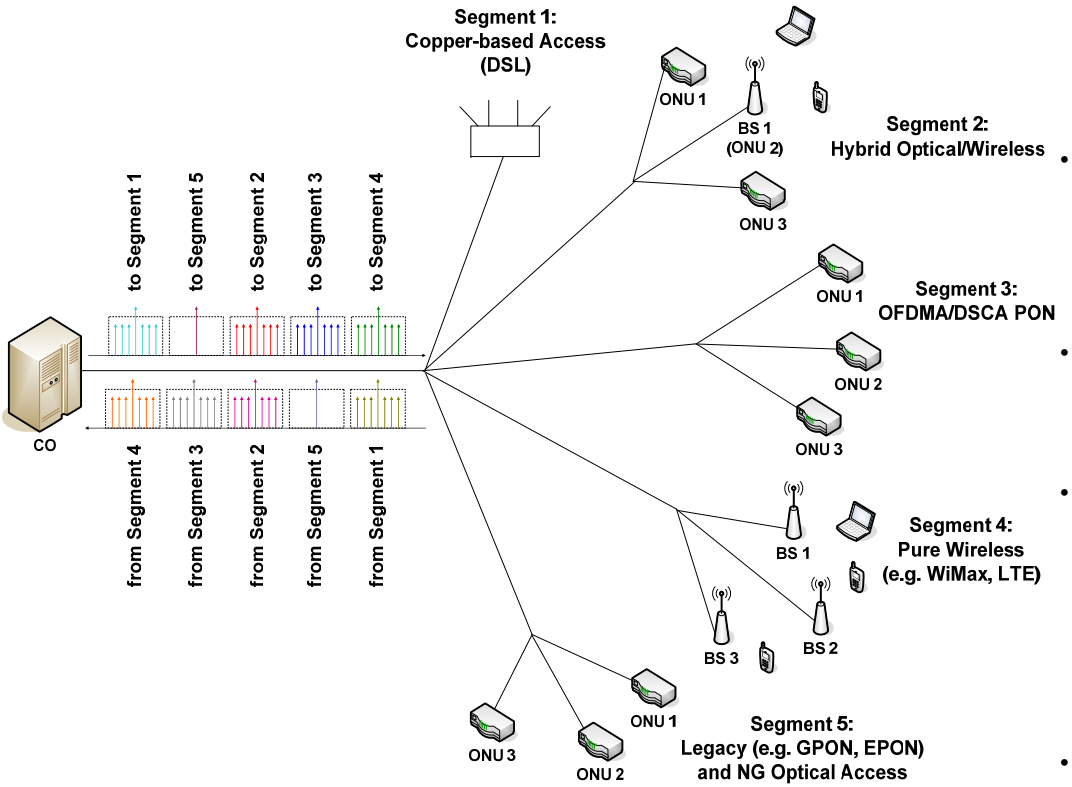
- **Provision of smooth migration from and coexistence with legacy access solutions.**
  - Definition of migration paths from existing access networks to the ACCORDANCE vision, reported in deliverable D2.3
- **Multi-operator, multi-service support.**
  - Detailed study on leveraging the ACCORDANCE FDM band overlay for supporting multiple providers
- **Contribution to standardization activities on Next Generation Optical Access.**
  - Participation in the standardization bodies on next generation access networks
  - Provide input to them from the ACCORDANCE research and influence them towards the ACCORDANCE concepts
- **Demonstration of the ACCORDANCE concepts using experimental test beds.**
  - Implementation of the ACCORDANCE nodes (OLT, ONUs)
  - Assembly of a functional test-beds using off-the-self components and specially programmed FPGAs
  - Service delivery over a final experimental test-bed
- **Dissemination of project results.**
  - Definition of a clear and effective dissemination plan
  - Publications in high quality journals/magazines
  - Presentations in high quality conferences/workshops
  - Web-site establishment

ACCORDANCE relevance to the FP7 call 4

- ACCORDANCE directly targets FP7 Challenge 1: “Pervasive and Trustworthy Network and Service Infrastructures” and in particular the Objective ICT-2009.1.1: “The Network of the Future”. The scientific and technical objectives set by ACCORDANCE are in line with ICT-2009.1.1.

  - **Convergence:** ACCORDANCE proposes an architecture which, through the use of combined FDM and OFDM multiplexing, can accommodate at the same time virtually any type of access technology (optical, wireless, copper) using the same infrastructure.
  - **Ultra-high capacity:** The ACCORDANCE network offers aggregate rates in the access network than can reach up to 100Gbps, with more than 10Gbps for each network segment.
  - **Low cost / low complexity:** The aforementioned bit rates can be achieved using low cost equipment and avoiding the need of complex burst-mode receivers typically required by high-bandwidth TDMA-PONs. Both facts owe to the OFDM concept of splitting the signal into multiple low-bandwidth sub-carriers.
  - **Multi-operator support:** The ACCORDANCE architecture is designed in such a way to facilitate the support of multiple operators within the same optical infrastructure, each of them using a different FDM band.
  - **Flexible bandwidth allocation:** ACCORDANCE offers the opportunity to conduct bandwidth allocation in multiple levels of granularity (FDM/OFDMA/TDMA).
  - **Extended reach:** The improved transmission properties of the individual OFDM sub-carriers enable the extension of the ACCORDANCE network to cover metro-sized areas at high split ratios.
  - **Energy efficiency:** This objective is addressed by the fact that the optical distribution network of ACCORDANCE is fully passive, while the extended reach of the network and the centralised wireless approach decrease the total number of power-consuming central offices.

ACCORDANCE network architecture



The ACCORDANCE network architecture is capable of supporting:

- *OFDMA/DSCA PONs*: The term implies network segments where individual sub-carriers of a FDM window are assigned dynamically to different ONUs of the segment, i.e. the multiplexing takes place at the sub-carrier granularity. It is possible though to follow TDMA approaches as well, so that each sub-carrier is shared among ONUs in the time domain.
- *Pure Wireless networks*: In this case a set of sub-carriers in a FDM window is dedicated to a group of wireless Base Stations (BS), which actually incorporate the functionality of an ONU as well. Then Radio-over-Fibre (RoF) techniques are used to carry the corresponding OFDM wireless signals through the optical infrastructure.
- *Hybrid Optical Wireless networks*: This type of access can be thought of a mixture of the two cases described above, whereby optical and wireless users are allowed to coexist and share the sub-carriers within the same FDM swindow.
- *Legacy or Next-Generation Optical Access networks*: In the case of legacy PON technologies like EPON or GPON, as well as of possible TDMA-based next-generation updates of those protocols, OFDM may only be employed as a modulation (potentially including an RF-to-digital converter) rather than multiplexing method (since all ONUs share the same downstream/upstream channel in a TDMA fashion), or not be employed at all (using for example conventional NRZ modulation, as is the case for Segment 3 of Figure 1).
- *Copper-based Access networks*: Even if DSL approaches become increasingly obsolete in the following years, it is still possible for the ACCORDANCE architecture to support them as well. This is achieved by using FDM windows as transparent pipes for transmitting the corresponding Discrete Multi Tone (DMT) signals up to the DSL users and vice versa.

ACCORDANCE Main Innovations

- The architecture proposed in the ACCORDANCE project covers all goals set by the upcoming standardisation efforts and recent research work on optical access networks.
- ACCORDANCE targets an unprecedented aggregate rate of 100 Gbps in the access network via the use of FDM multiplexing, i.e. by adopting a multi-wavelength way of operation.
- ACCORDANCE can provide a much finer granularity than typical WDM-PON approaches by subdividing the spectrum in low-bandwidth sub-carriers.
- The ACCORDANCE concepts facilitate the offering of the much-awaited ≥10 Gbps in individual FTTH network segments by employing OFDMA.
- OFDMA allows for the use of low-cost equipment and abolishes the need for sophisticated and costly burst-mode receivers which are inevitable in pure TDMA approaches.
- The improved transmission characteristics of OFDM allow for the extension of the access network to cover metro spans in a natural way.
- ACCORDANCE allows the seamless co-existence of optical and wireless technologies not only on the physical layer, but further employs a centralized scheme that enables controlling all end users from the same central office. This allows on the one hand the use of advanced wireless techniques (like Network MIMO) but also the dynamic sharing of resources at the MAC layer among all kinds of connections, either wired (including copper as well) or wireless, through the combined use of FDM bands and OFDM sub-carriers.
- In the centralized ACCORDANCE architecture, all information needed for interference optimized scheduling is available at the central office without the need for inter-base station communication as in pure wireless architectures. This eventually promises significant performance gains and reduced signalling overhead compared to any multi-site scheme.
- All the above facts indicate that ACCORDANCE can play a key role in the developments that will define the future of optical access networks.

ACCORDANCE Benefits (1/3)

- **Virtualization of Resources**
  - CO manages several Virtual PONs in different sets of sub-carriers (FDM overlay)
  - More services (e.g. ADSL and WiMax) supported within the same infrastructure

- **Dynamic Bandwidth Allocation**
  - Each ONU of a Pure OFDMA-PON gets dynamically sub-carriers allocated
  - Eliminates need for complex MAC schemes at OLT
  - DBA reduced to determining number of sub-carriers assigned to each user
  - No synchronization or overlapping avoidance needed
  - TDMA operation may still be desirable in the upstream

- **Novel business and tariff models**
  - Bandwidth allocated dynamically and upon request, at small or larger time scales
  - Users can “lease” more sub-carriers just for one day to stream HD movies, while normally a single sub-carrier enough for web browsing
  - Virtually any bandwidth amount available for a user if needed
  - Bandwidth thought of as a commodity rather than an offered service
  - No charging at all when no network resources used

ACCORDANCE Benefits (2/3)

- **Improvement of transmission properties**
  - Each of the sub-carriers transmitted has much lower bitrate than the aggregate
    - Less susceptible to impairments such as chromatic dispersion
    - OFDM modulated data can effectively travel longer distances
    - Larger user base covered by each OLT
    - 100km operation @ 4Gbps by using symmetrical ODFM-QAM with a split ratio of 256
    - 10 Gbit/s transmission has already been demonstrated without dispersion compensation
  - Higher spectral efficiency
    - Orthogonality of sub-carriers allows them to be spaced very close to one another
  - Flexible adaptive multi-user bit/power allocation per sub-carrier in addition to sub-carrier assignment possible
- **Cost-effectiveness**
  - Cost for ONUs to support 10Gbps with existing solutions may be prohibitive
  - Already available low-cost optical devices and electronics can be used

ACCORDANCE Benefits (3/3)

- **Wireline-wireless convergence.**
  - Wireless channels transmitted over fibre in dedicated FDM windows, or:
  - Different RF sub-carriers dedicated to wireless antennas in each ONU
    - Concurrent transmission of wireless channels for different network segments
  - Combined with optical packets and modulated onto the optical carrier
  - Centralized control from the CO
  - Efficient multiple channel allocation per wireless sectors
  - Potential support for mesh networking

- **Migration from Current Technologies.**
  - Highly forward-looking perspective for the access (Pure ODFMA-PON) but also:
  - Smooth migration from existing access technologies:
    - Current PON protocols (e.g. GPON/EPON or upcoming standard updates)
    - Copper-based solutions (e.g. DSL)
  - All through the same fibre infrastructure

Main Challenges (1/3)

- **MAC Layer**
  - Novel lightweight MAC algorithms for Pure OFDMA-PONs must be proposed
  - Dynamic bandwidth assignment of OFDM sub-carriers
  - Preferably minimal modifications to existing frame formats
  - Hybrid OFDMA/TDMA operation should be possible
  - Modification of MAC control mechanisms to include spatial besides time assignment

- **PHY Layer**
  - Decide on optimal optical devices and modulation formats
  - High Peak-to-Average power ratio (PAPR) due to large number of independent sub-carriers
    - Solutions from wireless OFDM research can be examined and be adapted to the optical case
  - Non-linearities of low-speed/low-cost OFDM devices
    - Linear equalization after IFFT in the transmitter could solve it
    - Usage of FEC to make the system more robust to non-linear effects.
  - Clipping or saturation avoidance: High power levels may be required in the fiber
    - Could potentially cause eye-safety issues.
    - However, several OFDM RoF architectures have shown good performance with modest power levels,

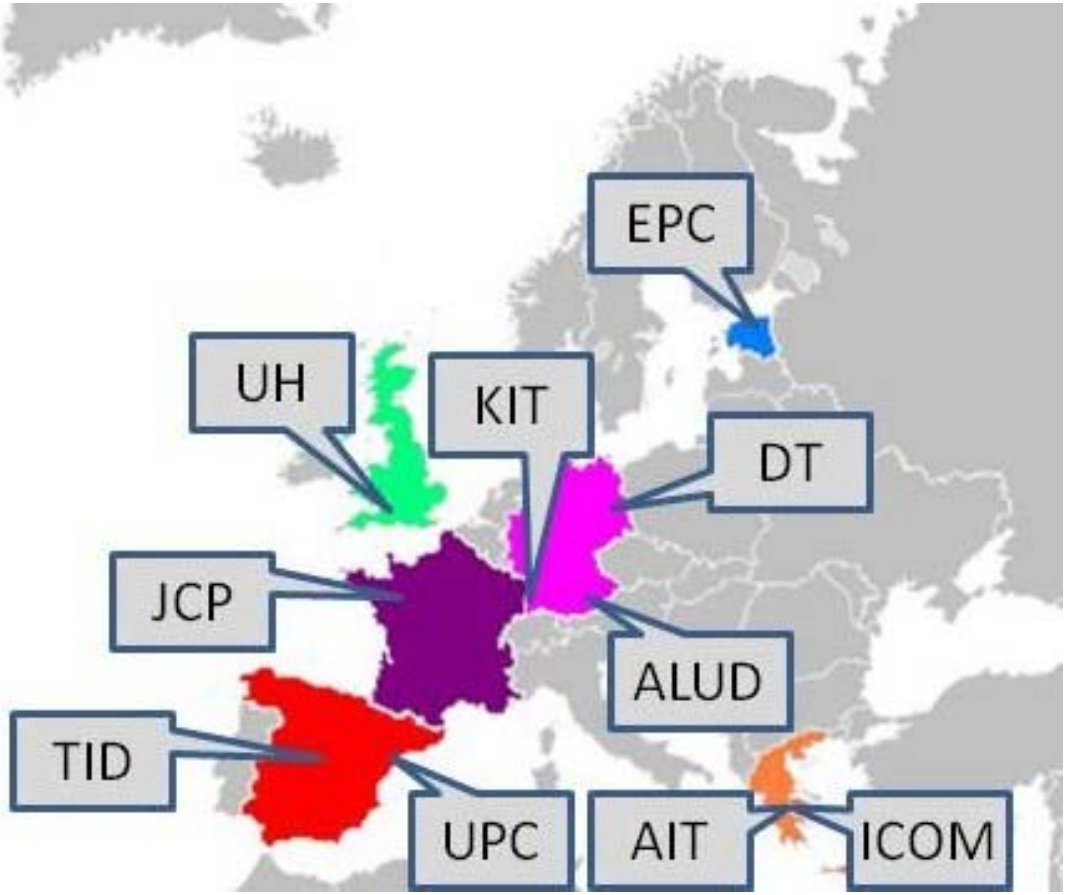
Main Challenges (2/3)

- **Upstream Direction**
  - ONUs required to work in slightly different wavelengths
  - Signal-Signal Optical Beat Interference (SS-OBI)
    - Find ways of minimizing OBI (e.g. use of low coherence sources like SLEDs), or else:
    - Limit maximum amount of usable sub-carriers in the upstream
    - Combined ODFMA/TDMA MAC minimizes both synchronization issues and OBI
  - General trade-off between supported sub-carriers and complexity of MAC
    - High number of sub-carriers:
      - Fine granularity with simple MAC (each sub-carrier operates at very low rates)
      - More challenging physical layer (e.g. OBI, non-linearities).
    - Lower number of sub-carriers
      - Reduced physical layer challenges and processing
      - TDMA operation necessary to enable sub-sub-carrier allocations
  - ONU processing for the entire OFDM stream is demanding
    - FDM multiplexing relieves problem to some extent, since:
    - Only a single component is extracted for further processing by each ONU using BPFs.

Main Challenges (3/3)

- **Optical/Wireless interoperability**
  - Straightforward solution:
    - Specific wavelengths or sub-carriers for the wireless transmission
    - OLT and ONUs zero those sub-carriers during OFDM modulation
    - Radio channels transmitted transparently via pre-established transmission pipes
    - Wireless and optical MAC layers do not interfere with one another
  - More advanced/complex solution
    - Wireless connectivity/mobility expected to be increasingly present in future access
    - Dynamically share sub-carrier bandwidth among wireless terminals and static ONUs
    - PHY and MAC jointly optimized based on individual link quality and data-rate per user

ACCORDANCE consortium



ACCORDANCE expected impact - I

- **Strengthened positioning of European industry in the field of Future Internet technologies and reinforced European leadership in mobile and wireless broadband systems optical networks cognitive network management technologies.**
  - The innovative concepts of ACCORDANCE are expected to give a boost in the field of optical and wireless networking globally, strengthening thus the position of Europe in those rapidly developing and challenging fields and expanding the scope of the European market to a worldwide scale.
  - ACCORDANCE, via its architecture which facilitates the support of multiple operators and multiple technologies within the same infrastructure in a flexible way, is also expected to provide a natural environment for healthy competition among European network and service providers that will revitalize the European market and reinforce its competitiveness.
  - A widespread adoption of the ACCORDANCE vision could contribute to the emergence of a large number of European Small & Medium Enterprises (SMEs) manufacturing relevant components and equipment. Such a development will be beneficial for the whole European industrial landscape, since those enterprises, by being smaller and thus more agile than well-established large companies, can bring in fresh ideas that will stimulate the European telecommunications market.

ACCORDANCE expected impact - II

- **Increased economic efficiency of access/transport infrastructures (cost/bit)**
  - ACCORDANCE actually retains this general PON topology which along with the totally passive nature of the Optical Distribution Network and the reduced number of ports at the OLT (compared to fibre point-to-point solutions), lead to an extremely cost-efficient network infrastructure.
  - ACCORDANCE adopts an OFDM approach whereby the signal is split in several low bitrate sub-carriers, which improves the signal transmission properties by making it less susceptible to impairments. In that way, OFDM modulated data of several Gbps aggregate rates can effectively span much longer distances and higher split ratios can be achieved. The end result is that each Central Office can cover a larger user base, reducing in this way the CAPEX and OPEX costs of the network. This leads to an infrastructure where the cost per bit will be significantly low.
  - The aforementioned properties of OFDM provide the opportunity to use already available low-cost optical devices and electronics. This is a very crucial issue, since the cost for upgrading ONUs to support the envisaged ≥10 Gbps rates with existing solutions may prove prohibitive, not only due to the high-speed electronics involved, but also because of the extremely challenging burst-mode operation required by the PON devices under the TDMA assumption. The latter issue is solved in ACCORDANCE by employing OFDMA to allow for multiple access of ONUs in the frequency domain. With the consumer demands, as well as the standardization activities already pointing towards data rates in the access of more than one order of magnitude higher than existing solutions, we believe that the ACCORDANCE concept will play a key role towards the realization of this goal in the most cost-efficient way for the end user.
  - Finally, the multi-operator multi-service concept of ACCORDANCE is expected to lead to a competitive business environment, which will bring as a natural result the desired reduction of cost/bit for the consumers.

- **Global standards, interoperability and European IPRs reflecting federated and coherent roadmaps.**
  - The industrial partners (ALUD, DT, TID and ICOM) of the ACCORDANCE consortium will lead the exploitation initiatives while providing a fast-track exploitation route where appropriate to market requirements and are committed to be active in standardization. In particular, the industrial partners are part of working groups of the wireline and wireless standards bodies like: ITU-T and FSAN (GPON), IEEE802.3 (EPON) which have begun studies towards Next Generation Network (NGN) PON networks even beyond 10 Gbps, as well as in ETSI, IEEE 802.16m (WiMAX) und 3GPP (LTE advanced).
  - Active involvement of the partners in those standardisation bodies will, on the one hand ensure awareness of the consortium about the most recent evolution trends in commercialisation of access technologies and on the other allow the ACCORDANE consortium to provide input and significantly influence the relevant standards. The latter is actually one important goal set by ACCORDANCE, since we believe that the proposed topology meets all necessary requirements for becoming the access network infrastructure of choice to support Future Internet.

ACCORDANCE expected impact - III

- **Wider market opportunities from new classes of applications taking advantage of convergence.**
  - The ACCORDANCE network, with the ultra high capacity capability and effective management of dynamic traffic patterns and service differentiation it offers to the access network will enable a significant enhancement of the overall volume of data-centric traffic.
  - ACCORDANCE provides an efficient solution for ubiquitous access by offering the opportunity to dynamically allocate bandwidth for wireless traffic over the optical network, as well as by adopting a centralized wireless scheme that has the potential to significantly enhance wireless connection quality.
  - The ACCORDANCE concept of communicating advanced ICT services over wireless media is also a critical consideration for developing countries. A sort of “wireless triple play” can significantly enhance access to services and content for rural or hard-to-reach communities. The number of mobile subscribers in developing countries is significantly higher and far more diffused than the number of personal computer users. ACCORDANCE can hence facilitate the offering of broadband connectivity and services to a far larger proportion of the population, developing a significant social and economic transformation in Europe.

- **Accelerated uptake of the next generation of network and service infrastructures.**
  - ACCORDANCE has the ability of offering end users access to content and services through a variety of networks and platforms, both wireline and wireless. This flexibility is expect to facilitate the adoption of this next generation network/service infrastructure by the new breed of customers who, mainly due to the widespread success of mobile telephony, are accustomed to enjoying services at any location and using a variety of end devices apart (with desktop computers tending to become the minority).
  - In addition, both the longer network reach achieved by the optical infrastructure of ACCORDANCE, as well as the support for the next generation of wireless access technologies, will enable the provision of high-capacity connectivity to users in rural and sparsely populated areas. This will eventually help in bridging the gap of broadband adoption among geographic areas and consequently accelerate the uptake of next generation networks across Europe.
  - ACCORDANCE users will have the freedom to select among a wider range of services and choose among more operators and service providers. On the other, the increased offered bandwidth and allocation flexibility of the ACCORDANCE network will allow service providers to develop new business models and offer completely new services which will in turn attract a completely new customer base.

Thank you for your attention!