The Future of Ultrabroadband Communications: a Roadmap to NGAN

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Abstract — The paper describes some relevant solutions for Next Generation Access Network (NGAN, or NGN), considering evolution from copper legacy network to optical access network (PON, Passive Optical Network) and analysing pros and cons of several PON solutions (TDM-PON, WDM-PON, TWDM and OFMD-PON) as well as potential convergence/coexistence scenarios.

Keywords—copper network; NGAN; PON; GPON; XG-PON; TDM-PON; WDM-PON; TWDM-PON; OFDM-PON;

I. EVOLUTION OF COPPER NETWORKS

In the last years several techniques (e.g., bonding, vectoring, phantom mode) have been developed to increase the performance of xDSL (Digital Subscriber Line, providing maximum 100 Mbps for single line), widely used in copper networks [1].

Currently the G.fast technology is under standardization at ITU, based on the mentioned technologies allowing copper networks to provide “up to” 1 Gbps symmetric (downstream and upstream) bitrate per user on short loops within 250 m, i.e. for access network in FTTB (Fiber-To-The-Building), FTThp (Fiber-To-The-distribution-point) or FTTC (Fiber-To-The-Cabinet) architectures (see Fig.1) [2, 3].

Fig.1. Main FTTx architectures.

Although G.fast seems rather promising, it is hard to believe that 1 Gbps (or more) can be provided to every user in every country / area with copper networks, since there will always be areas with “local loops” longer than 100 m – the length of “last mile” greatly influences performances. Moreover, the vectoring technique is not compatible with LLU (Local Loop Unbundling) since different lines / signals of the same DSLAM (Digital Subscriber Line Access Multiplexer) can belong to different Operators: vectoring performs a pre-distortion (“pre-compensation”) of all signals / lines belonging to the same DSLAM in order to reduce noise and interferences (mainly crosstalk).

Furthermore, new broadband services / applications are getting to the market (e.g., Digital TV HD and 3D, HD video-communications, e-health, e-learning, online interactive games, cloud computing, immersive / virtual reality), and copper (even with technology evolutions) is likely not able to support these services or to enable the birth of others needing very broadband.

Therefore, it is mandatory to plan an entirely optical access network (FTTH / FTTB) for the near future, providing at least 1 Gbps per user. In the following, FTTH configurations are considered – unless otherwise specified.

1 With VDSL2 (Very-High-bitrate DSL 2).
2 1 Gbps over short distances (50-100 m), some hundreds of Mbps for longer spans (within 200-250m).
3 Fiber reaches user’s building (few tens of meters far from final users).
4 Fiber-to-the-home: fiber is terminated on the user’s home (usually in a box on the outer wall) – no copper wires used.
5 There are several EU study groups focusing on next generation PON solutions; in particular, the FSAN (Full Service Access Network) has outlined a NGN-roadmap to evolve the current PON systems onto NG-PON1 first (abandoned afterwards) and then onto the NG-PON2.
II. PON (Passive Optical Network)

While for business customers it is reasonable to consider P2P (Point-to-Point) solutions, whereby each user has a dedicated optical link with Central Office (CO) like in copper networks, for residential customers it has been demonstrated that P2MP (Point-to-multi-Point) solutions – where a single fiber link is shared among multiple users – are more convenient and provide adequate performance. A study case performed in Lombardy region by the NGN Italy Committee has shown that a P2P solution would cost about 70% more than a P2MP solution (GPON) [5].

The most adopted P2MP solution is the PON (Passive Optical Network), where the ODN (Optical Distribution Network) is entirely passive\(^7\). The most installed PON is the GPON (Gigabit PON), characterized by 2.5 Gbps downstream and 1.25 Gbps upstream aggregated bitrates for a single fiber link, shared usually among 32 users\(^8\) (thus providing 80/40 Mbps downstream / upstream to each user). The GPON solution allows providing triple-play services (i.e., phone, Internet, TV) using 3 wavelengths: 1490 nm (downstream), 1310 nm (upstream) and 1550 nm (video overlay). Since GPON is based on TDM (Time Division Multiplexing), it requires a MAC (Medium Access Control) to avoid upstream collisions. OLT (Optical Line Termination) transmits downstream signal broadcast to every ONT / ONU\(^9\) and they read only their respective packets. In the upstream direction, each ONU has a “grant” to transmit only in specific time windows. In the last years the XG-PON1 (or 10G-PON) solution has been developed, that upgrades (and can coexist with) legacy GPON systems, providing 10 Gbps downstream and 2.5 Gbps upstream [6].

One of the disadvantages of TDM-PON solutions concerns unbundling\(^10\); since each optical link is not dedicated to a single user (like in copper networks or in P2P optical networks), it is not possible to provide LLU. Although there are other options to perform unbundling (e.g. bit-stream), the possibility of providing LLU is a key factor to conciliate different Operators’ interests and to unlock the realization of NGANs. There are several options, like WDM-PON (Wavelength-Division Multiplexing-PON) and OFDM-PON (Orthogonal Frequency-Division Multiplexing-PON), allowing a “virtual” access to the physical medium using wavelength division: as a matter of fact, it is possible to assign a single wavelength / channel (or a group of channels) to a specific operator, sharing the same physical medium among multiple operators. A current and complete overview of LLU for European market is in [7].

Key factors for next generation access solutions are: ability to operate on existing ODN (ODN reuse), support of LLU and broadcast-and-select (possibly up to eight independent Operators) and compatibility with video overlay and XG-PON1 systems.

III. WDM-PON

The most presently installed PONs are based on TDM multiplexing (GPON), where all users share a single pair of wavelengths (downstream and upstream\(^11\)).

With WDM-PON it is possible to assign a single pair of wavelengths / channels (upstream and downstream) to each user (or group of users). The number of available channels may vary from 8\(^12\) with CWDM (Coarse WDM) to 40 / 80\(^13\) with DWDM (Dense WDM) up to 160\(^14\) with UDWDM (Ultra Dense WDM).

This multiplexing allows very high performance (bitrate about 1Gbps per user\(^15\) symmetric, maximum reach even more than 40 km) at the expenses of increased complexity and costs.

Moreover, WDM allows to realize LLU (unbundling at the CO\(^16\)) allocating a single pair of wavelengths (or a group of) to each Operator. Since wavelengths/channels are independent, it is possible to share the same ODN between business users (who may need a dedicated channel for high bit rates) and residential users (who may share one channel).

There are two main ways to realize WDM, depending on splitting devices at the ODN:

- “wavelength-routed” (or “pure WDM”): power splitters are substituted by AWGs (Arrayed Waveguide Grating), that can perform wavelengths splitting (de-mux WDM) in the downstream direction and wavelengths merging in upstream (mux WDM)\(^17\). In this configuration, each ONU receives only its channel (see Fig.3) [8].

- “Broadcast-and-select”: in this case, the same “power splitters” of TDM-PONs are used. The downstream signal is broadcasted onto every ONT (every channel sent to every

\(^7\) After OLT only fiber links and power splitters are used, without signal amplification or regeneration.
\(^8\) It is possible to use higher split ratios (theoretically till 1:128), but rarely used because of its huge impact on maximum reach.
\(^9\) The term ONU (Optical Network Unit) is used for FTTH configurations, and the term OLT (Optical Line Termination) is used for FTTH (Fig.1). In the following, the term ONU is used for the sake of simplification.
\(^10\) The incumbent Operator, that built the access network, has to allow other operators (OLO, Other Licensed Operators) to provide Internet service to customers using a part of the existing network.
\(^11\) Theoretically is possible to use a single wavelength for both directions, but there are strong limitations due to backscattering phenomena (Rayleigh and Brillouin). For this reason, the most used systems are based on 2 different wavelengths / channels. Moreover, in some case a 3rd channel is used to provide TV service (e.g. GPON).
\(^12\) Traditional WDM uses 16 channels, but in order to realize cheaper ONUs, CWDM adopts a wider spacing (between 2 adjacent channels) and eliminates the attenuation window in the 3\(^{rd}\) window, thus allowing only 8 channels.
\(^13\) Depending on adopted frequency spacing: 100 GHz spacing (40 channels), 50 GHz spacing (80 channels).
\(^14\) 25 GHz frequency spacing.
\(^15\) Aggregated bitrates 16-32 Gbps.
\(^16\) It is like having a system “virtually” P2P, since each user can be managed individually through its wavelength / channel. An Operator is able to allocate a single channel to each user (or group of users) and can easily re-allocate and modify bitrates assigned to single users.
\(^17\) AWG is also called “WDM router”.

![Fig.3. “wavelength-routed” WDM-PON](image-url)
user) and each single ONT has to select only its channel (see Fig.4).

Fig.4. “broadcast-and-select” WDM-PON

The “wavelength routed” approach allows having a better power budget (since AWG has a fixed attenuation independently of number of ports\(^ 18\)) and therefore a longer reach (some experimental test reached 100 km). Moreover, downstream signals are automatically filtered for ONTs at the RN (Remote Node), where AWG is placed. On the other hand, this approach does not allow coexistence (and smooth migration) with legacy systems (GPON / XGPON1) or other systems on the same ODN, needs interventions on existing ODN and is not very flexible (changes to frequencies assigned to each user, switching to other Operators, etc).

Instead, the “broadcast-and-select” approach is compatible with other systems (legacy included) on the same ODN, does not need interventions on existing ODN (protecting investments) and is very flexible. On the other hand, maximum reach is shorter (because of the lower power budget) and it is necessary to realize an accurate filtering on each ONT, thus increasing cost and complexity of ONTs.

In both cases, the transition to WDM-PON forces to develop low-cost colourless ONTs (both transmitter and receiver have to be tuneable), that are not characterized by a fixed operating wavelength and are able to modify his operational channel if needed (e.g. Operator change) \([9]\). The most promising technologies for transmitters are:

- Laser Tuneable (e.g. DBR, DFB, and ECL\(^ 19\)): lasers that allow to change wavelength, modifying some parameters (temperature, electric current, mechanic movements, etc.). This class has generally very high performance (bitrate, reach, etc.) but also high cost. An exception is ECL, convenient but with stability issues at high bitrates. Other advantages are that tuneable lasers do not need an external seed signal from OLT and are resilient to environmental conditions (temperature, backscattering, etc.) \([10, 11]\).

- IL-FP (Injection Locked-Fabry Perot) lasers, that are driven by a narrowband seed signal (from OLT). The injection of a strong pump signal at a determined wavelength locks FP on that wavelength. Although costs are low, performances are limited and it is necessary to provide a strong non-modulated seed / locking signal (e.g. through a BLS\(^ 20\) at the OLT plus an AWG in the ODN\(^ 21\) that slices the signal, see Fig.5). A possible variation is named “self-seeding”, where a semi-reflecting mirror is used (placed right before AWG) to reflect part of the power towards IL-FP, thus avoiding the need of an external seed from OLT, but usually achieving worse performances \([12]\).

- R-SOA (Reflective-SOA): a SOA (Semiconductor Optical Amplifier) and a reflecting mirror are used in order to reflect and amplify the received signal on the same wavelength. There are three possible configurations: with a non-modulated seed signal from OLT (like IL-FP), with “self-seeding” architecture (like IL-FP) or performing a re-modulation of downstream signal (see Fig.6). In this last case, there can be some issues to delete downstream pattern. R-SOA has a cost not particularly low and is affected by environmental conditions (temperature, backscattering, etc.), with good performances but inferior to tuneable laser (being limited by chromatic dispersion). This solution is particularly interesting because there is no light source at the ONT and can be used without a seed signal \([13, 14, 15]\).

\(^{18}\) While an AWG has a fixed attenuation of few dB, a 1:N passive power splitter splits input power onto the N ports / exits, thus leading to higher attenuation (e.g. a 1:32 splitter has at least 15 dB attenuation).

\(^{19}\) Distributed Bragg Reflector (DBR), Distributed FeedBack (DFB) and External Cavity Laser (ECL)

\(^{20}\) Broadband light source: LED or ASE produced by an EDFA amplifier (Erbium Doped Fibre Amplifier).

\(^{21}\) “wavelength-routed” WDM.
About receivers, it is important to underline that for “broadcast-and-select” approach it is necessary to provide ONTs (or power splitters) with expensive tuneable BPFs (Band-Pass Filters), or use mechanisms that allow filtering of received channels (downstream) and to transmit (upstream) narrowband signals to avoid interference among upstream signals from other ONTs. One possibility is to adopt the coherent detection: input light (downstream signal) is superimposed to a LO (Local Oscillator) laser creating a light component on PD (PhotoDiode) proportional to the product of input optical field and the one generated by LO. This term oscillates with the difference of the two fields and, if this difference is within few GHz, the signal on PD has a frequency limited to the bandwidth of the detector. Thus, using a coherent detector is like providing the receiver with an optical amplifier and a very narrow band bandpass filter. The amplification allows having a very high power budget / maximum reach (up to 100 km) without needing optical amplifiers “in the field”. At the same time, the bandpass filtering allows to eliminate WDM filters at splitter sites, and the high selectivity allows to greatly increase the numbers of channels (up to thousands of users on each fibre), even though, for resilience reasons, Operators will rarely exceed a thousand users per fibre. Indeed, the coherent detection allows improving several aspects: receiver sensitivity, maximum reach, spectral efficiency and number of users per fibre.

Indeed the WDM “broadcast-and-select” approach seems very promising (and has more benefits than pure WDM). Since the system is more flexible, ODN can be shared among different PON systems (see Fig.7a) and / or different Operators (ULL, see Fig.7b), a smooth migration is possible from legacy PON to NG-PON and existing ODNs are totally reused. Power budgets can be improved by using advanced techniques (e.g. coherent detection) and technologies (e.g. tuneable lasers). As a matter of fact, the NSN’s (Nokia Siemens Networks) NGOA (Next Generation Optical Access) solution has demonstrated the feasibility of a bidirectional UDWDM system symmetric at 1 Gbps per user, over a 100 km maximum reach and allowing sharing of same fiber between 1000 users [10].

IV. TWDM-PON

This solution is based on a hybrid Time and Wavelength-Division Multiplexing (TWDM) and has been selected by FSAN as the NG-PON2 solution. The TWDM-PON stacks 4 XG-PON1s (4 pairs of wavelengths) using WDM, reaching an aggregate bitrate of 40 Gbps downstream and 10 Gbps upstream. There are also options to support 8 pairs of wavelengths in order to adapt to broader market scenarios (up to 8 independent Operators). The ODN remains passive since both the optical amplifier (to achieve a higher power budget) and WDM mux / de-mux are placed at the OLT side, and ONTs are provided with tuneable transmitter and receivers. This solution is compatible with GPON, XGPON1 and with video overlay on the same ODN, and allows to provide LLU, assigning one of the 4 XG-PON1 to each Operator (that will install its OLT at the CO). The feasibility was already demonstrated with a full prototype system that supports 20 km distance with a 1:512 split ratio (that can be converted onto a 1:128 split ratio with 40 km or a 1:64 split ratio with 60 km) [16]. It is worth underlining that this solution is well suited for the near future since it offers certainty (being based on XG-PON1 and other mature technologies) and CapEx savings to Operators that want to invest on NG-PONs in the next few years. On the other hand it does not allow to achieve the same distances (100 km) and performance (1 Gbps symmetric per user) offered by WDM solutions, necessary to achieve “node / exchange consolidation” and to provide very high bitrates to single users.

Fig.7. “broadcast-and-select” WDM with ODN sharing among different PON systems (a) and different Operators (b)

V. OFDM-PON

OFDM (Orthogonal Frequency-Division Multiplexing) is a multiple carrier technique widely used in various contests: digital terrestrial broadcast video (DVB-T) and audio (DAB), wireless transmissions (IEEE 802.11 e 802.16), 4G mobile systems (LTE, long term evolution), etc [17]-[19].

Data are transmitted simultaneously on several orthogonal sub-carriers (each has a low symbol rate in order to have a high symbol period and thus a low ISI) in order to eliminate /reduce crosstalk and using a guard time (between two symbol period) to avoid residual Interferences.

OFDM technique is realized through DSP (Digital Signal Processing) blocks that implement (usually electrically) the

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22 Moreover the LO laser can be a low-cost tuneable (e.g. ECL) in order to change the wavelength of the receiver.

23 E.g. if 4 XG-PON1s are assigned to 4 Operators and a 1:32 split ratio is used, every user can reach up to 310 / 80 Mbps downstream and upstream.

24 Especially for its robustness to ISI (Inter-Symbol Interference) caused by a dispersive channel.
DFT (Discrete Fourier Transform) to realize demodulation and demultiplexing of signal through a FFT (Fast Fourier Transform) algorithm. To perform this in a PON it is necessary to provide the receiver with DSP blocks that realize the DFT and the transmitter of DSP blocks that realize the IDFT (inverse FFT). There are two possible ways [20]:

- DFT implemented electrically (RF-OFDM, Radio-Frequency OFDM): it is necessary to use ADC (Analogue to Digital Converter) and DAC (Digital to Analogue Converter) able to operate at very high sampling rates. RF (Radio Frequency) converters are really expensive and should be used in both ONT and OLT, thus greatly increasing cost and complexity of system. Feasibility was already demonstrated, achieving a 10 Gbps bidirectional transmission with direct modulation of optical source [21].

- DFT implemented optically (AO-OFDM): there is no need of complex/expensive converters, since the transmission remains in the optical domain. Also in this case there are already feasibility demonstrations: there are several experimentations, among which one based on a planar passive patented by University of Roma Tre [22], and another achieving a record transmission of 26 Tbps [23].

OFDM technique has several pros:

- It increases spectral efficiency and is robust to ISI, chromatic dispersion, intermodal dispersion and other non-linear effects (e.g., Rayleigh backscattering).
- It is possible to integrate OFDM systems with legacy TDM systems (such as GPON) in order to allow a smooth migration to NG-PON2 systems.
- It is compatible with WDM: the feasibility of hybrid WDM-OFDM systems operating at 1.2 Tbps has been demonstrated [24].

VI. CONVERGENCE SCENARIOS

It is important to underline that optical access networks can enable/facilitate convergence scenarios, like the realisation of a single access network (sharing of ODN) for different kinds of users (business, residential and wireless26, see Fig.8) or realisation of “converged” FiWi (Fiber-Wireless) access networks (see Fig.9). The FiWi can be the “end game” of broadband access because combines pros of fixed connectivity (high performances and robustness) with the pros of the mobile (flexibility and mobility) and allows realizing Fi-WSNs (Fiber-Wireless Sensor Networks) even applicable to “smart cities and “smart grid” scenarios [25].

VII. CONCLUSIONS

In this paper, we have explored various solutions for NGAN from legacy copper network to optical solutions. In particular, we have shown that existing copper networks (even considering new techniques like vectoring) is not suitable to provide about 1 Gbps per user, necessary to enable new generation services (ex. Digital TV HD and 3D). Although technologies like G.fast can help to meet Horizon 2020 goals and reduce “digital divide” in scarcely populated areas (or with low economic interest/return), it is mandatory to consider investments in entirely optical access networks (i.e. FTTH or FTTB). The most used optical solution is based on TDM multiplexing (i.e. GPON), but has several limits (performance and unbundling). To overcome these limits, we explored WDM-PON (particularly promising with the “broadcast-and-select” approach, which allows more flexibility and “open/shared access” to ODN, thus enabling smooth migration and coexistence on the same ODN of different PON), TWDM and OFDM-PON (particularly promising with the AO-OFDM approach, that allows to avoid to use complex/expensive ADC/DAC converters). While for the short-term the TWDM (solution selected by FSAN for NG-PON2) can be a good choice to upgrade GPON/XG Pon1 and allowing LLU, in the long-term it is forward-looking to consider solutions based on WDM (like NSN’s NGOA) and or OFDM, keeping investing into colourless technologies/techniques (particularly promising are the ones based on R-

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25 All-Optical OFDM
26 mobile backhauling

27 OFDM and WDM can coexist on the same system.
SOA, ECL tuneable laser and coherent detection) and devices/techniques to implement OFDM entirely in the optical domain (AO-OFDM).

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