Investigation of Wavelength Control Methods for Next Generation Passive Optical Access Networks

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Abstract *We present a study on wavelength stability requirements for next generation passive optical network (PON) access systems in the light of induced timing jitter. Based on these findings different realization options of wavelength control methods for use in wavelength tunable PON systems are investigated.*

Introduction

In the past, several passive optical network (PON) architectures and technologies have been proposed[1]. Whereas currently deployed PON systems are mostly relying on time division multiple access (TDMA), there are several flavors of next generation PON under discussion[2] such as wavelength division multiplex PON (WDM-PON)[3] or time and wavelength division multiplex PON (TWDM-PON)[4]. These systems not only operate on a single wavelength, which is shared by all customers, but rather rely on an increase in capacity by using a multitude of different wavelengths and potentially stacking of multiple TDMA PON systems on certain wavelengths. Such next generation optical access (NGOA) systems (compare Fig. 1) will operate at bit rates of 10 Gb/s or even higher[4]. A key requirement for the mass-deployment of WDM techniques in a PON system is the availability of low-cost optical network units (ONU) tunable to the desired upstream wavelength[3].

In this paper we investigate the requirements for wavelength stability in such NGOA systems. Accurate wavelength control will be mandatory not only to avoid interference between WDM channels but more importantly to limit bit jitter and wander stemming from wavelength de-tuning, which is converted to timing jitter by the chromatic dispersion (CD) of the fiber. We show how different wavelength controlling schemes may be implemented for WDM NGOA architectures and discuss limitations and implementation issues.

Requirements on timing accuracy

In fiber-based transmission systems the residual CD leads to conversion of wavelength variations to timing jitter ($\Delta t = D_{SSMF} \cdot \Delta\lambda_{jitter} \cdot l_{reach}$). A future TWDM-PON system will operate with 200 GHz channel spacing (and potentially use several WDM channels also for uplink). This implies that wavelength variations can be within ±0.6 nm without WDM channel interferences. The amount of the resulting timing jitter can be approximated under the assumptions $D_{SSMF} \approx 17$ ps/nm/km (C-band), $l_{reach} \approx 60$ km and $\Delta\lambda \approx 1.6$ nm (max. variation within passband ≈ ±0.6 nm). A laser (not tightly locked to the desired wavelength) may thus induce a timing jitter of approximately ±600 ps. This corresponds to a variation of more than ±6 bit unit intervals (UI)

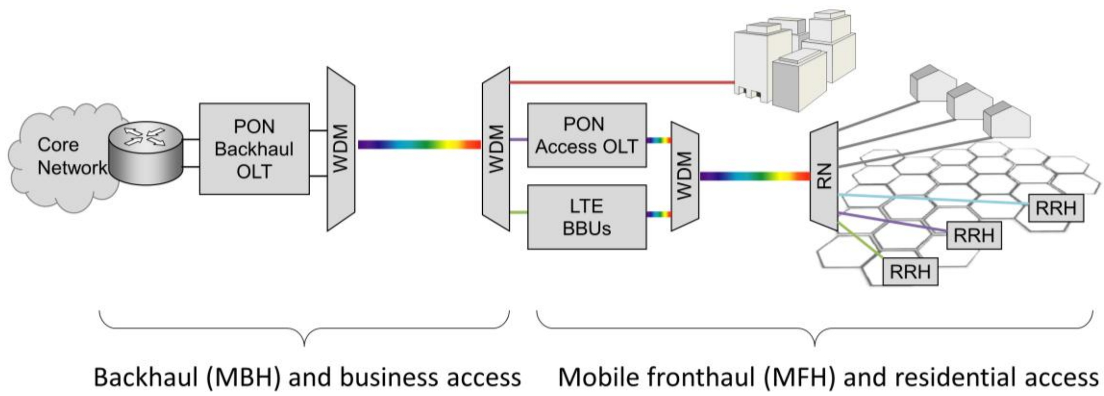

Fig. 1. Exemplary next generation optical access architecture for combined use in business and residential access as well as mobile backhauling (OLT: optical line terminal, BBU: base-band unit, RN: remote node, RRH: remote radio head)

assuming a PON operating at 10 Gb/s line rate. This may lead to a number of issues, which are summarized in the following.

ITU-T recommendation G.987.3 currently suggests a drift of window (DOW) of ±8 bits for an XG-PON system[5], accounting for the effects of aging, temperature change, etc. When this DOW is exceeded, an equalization delay adjustment is initiated. A drift of more than ±16 bits leads to a transmission interference warning and potential deactivation of the offending ONU. The timing is crucial in TDMA systems as the OLT expects the ONU's upstream transmission to arrive at a scheduled time during the upstream frame. An additional timing jitter due to wavelength instability is not accounted for in the above ITU-T recommendation so far.

Another requirement for timing accuracy comes from synchronization specifications, which are mandatory e.g. for mobile backhauling applications[6]. In current 3G networks, the reference clock for base stations is usually distributed via the global positioning system (GPS). For next generation mobile networks (e.g. long-term evolution, LTE), the reference clock will be distributed via the packet-switched backhaul network. This will require physical synchronization support (e.g. Sync Ethernet) or packet-based methods (e.g. IEEE 1588v2) to enable precise timing[6]. In LTE services, the air interface needs a synchronization accuracy of 2.5 µs. This already leads to a network infrastructure packet timing requirement in the sub-microsecond regime. Longer term, the timing accuracy is expected to be further increased significantly. In ITU-T rec. G.8261 Amend. 1, the amount of maximum permissible jitter is specified[7], which should not exceed 1.5 UI (corresponding to $\Delta\lambda \approx \pm 0.07$ nm wavelength jitter based on the above assumptions) measured in a bandwidth of 20 kHz – 80 MHz. Slow jitter (in the lower kHz region) will be effectively filtered by the Ethernet equipment clock (EEC) and will likely not affect the signal. Usually, the clock distribution is done from a primary reference clock in downstream direction. There may, however, be scenarios, where synchronization is needed in the uplink path of a network, for example, if a high precision clock signal obtained from e.g. a DCF77 signal is fed into the network at a certain mobile base-station (or ONU) and is distributed afterwards through the network.

Last but not least an abrupt timing shift of several UI (which can be induced by e.g. a mode-jump of a laser) will lead to unlocking of the (timing-recovery) clock. This will lead to an error burst and may require re-transmission of the affected data frame.

Wavelength control schemes

One of the most important components of a wavelength-tunable PON system is the cost-effective colorless ONU transmitter sub-assembly. To significantly reduce CapEx and energy consumption (and as well the associated operational cost), the ONU laser may be realized without a thermo-electric cooler (TEC) and be based on a high-temperature substrate. Furthermore, additional CapEx savings can be gained, if the wavelength locker is omitted. To stabilize the wavelength of the ONU, however, feedback on the actually emitted wavelength has to be provided. The required control signal can either be generated at the OLT or in the ONU itself as shown in Fig. 2.

First, OLT-based wavelength control is discussed in the following. The simplest way of calculating the frequency deviation of the ONU would be to merely measure the power of each WDM channel after demultiplexing at the OLT. This approach assumes that the output power level of the tunable laser is fixed relatively well, and thus a decrease in power correlates to a mistuning of the laser. In this case the measured attenuation is caused by the transfer function of

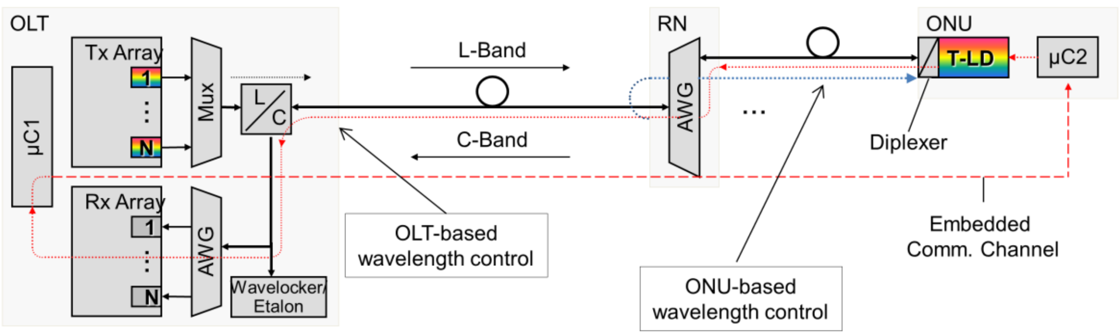

Fig. 2. Visualization of OLT- and ONU-based wavelength control schemes (OLT: optical line terminal, RN: remote node, AWG: arrayed waveguide grating, ONU: optical networking unit). Dotted lines: Path of optical signal: blue: ONU-based detection, red: OLT-based dectection. Dashed line: path of wavelength feedback signal (only for OLT-based detection)

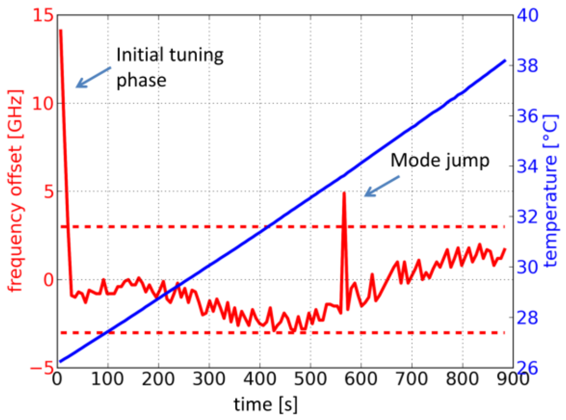

Fig. 3. Time evolution of ONU frequency offset under the impact of temperature changes[8]. Wavelength control was performed using a wave locker located at the OLT

the AWG. The method is severely limited as output power variation of the laser has to be kept in a very low region to be able to provide accurate control information when approaching the edges of the passband. In general this method will lead to a considerably high frequency deviation (in the range of at least the passband of the AWGs) around the desired target center frequency and provides better feedback information in dense WDM with relatively small passband width.

A more precise realization of an OLT-based wavelength control is the use of a single (centralized) wavelength locker in the OLT to provide feedback information on both frequency and power to all attached ONUs. To distinguish between the different WDM channels pilot tones can be used, which are modulated with a different frequency for each channel[8]. As shown in Fig. 3 this method allows keeping the variation of the channel frequency in a target range of ±3 GHz (after the initial tuning phase). Only mode jumps may lead to a short overshoot out of this interval (which may be reduced with a tuning algorithm maximizing the mode hop free range[9]).

Due to the propagation delay (for a full roundtrip of up to approx. 120 km) OLT-based wavelength control cannot operate faster than on a millisecond timescale. To provide the feedback path to the ONU either out-of-band communication (e.g. via a pilot-tone based ECC) or in-band communication in the form of control frames may be used.

Alternatively ONU-based wavelength control methods can be realized, which detect back-scattered or reflected portions of the upstream signal. The detection of the control signal directly inside the ONU has the advantage of avoiding a control channel to transport the (detuning) feedback information back to the tunable laser. It clearly improves latency in the control loop (by a factor of approx. 10 assuming that a feeder fiber typically is 90% of the total length) as the feeder fiber does not have to be passed twice.

A possible realization of this approach is to monitor the power of Rayleigh-backscattered light[10], which has passed the AWG in the remote node twice. To improve this method the wavelength of the laser may be dithered by a low frequency sinusoidal current, which is converted to amplitude modulation (AM) in the remote node AWG. This AM is Rayleigh-backscattered and can be detected by a low-speed photo diode at the ONU. Control of the wavelength within a ±2.5 GHz target interval has been shown with this method[10] (using an AWG with 50 GHz channel spacing).

Instead of relying on Rayleigh-backscattering of the signal, a periodic reflective filter may be deployed at the common port of the AWG. This realization has the advantage that the reflective filter potentially offers a higher accuracy especially in systems operating on coarser channel spacing. It also provides a stronger feedback signal (given e.g. 5% reflectivity).

Conclusions

We have shown a study on wavelength stability requirements in NGOA networks with tunable laser sources. To avoid timing jitter induced network operation problems, the laser wavelength should be kept in an interval of e.g. $\Delta\lambda \approx \pm 0.07$ nm which is much smaller than the frequency spacing of the WDM channels, and fast wavelength jumps should be avoided.

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