Will it be easy for the telecom carriers to deploy 40Gb/s transmission systems?

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Abstract. *Due to advances it 40Gb/s technology, the telecom carriers will experience the transition to the next generation fiber optic transmission systems based on 40Gb/s technology as trivial in comparison with the previous transition from 2.5Gb/s to 10Gb/s.*

The capacity of fiber-optic communication systems has been growing tremendously over the past years. In this process, the telecommunication carriers have gone through major changes in the network design such as the introduction of in-line optical amplifiers and the transition from single-wavelength transmission to multi-wavelength transmission (also called wavelength division multiplexing, WDM). At the same time, the per-channel electrical time-division multiplexing (ETDM) data rate of commercially deployed transmission systems has been increasing approximately by a factor of four every five years. During the last transition of ETDM rates from 2.5Gb/s to 10Gb/s, the service providers furthermore had to adopt another new concept in their optical networks: in-line dispersion compensation. This required placement of bulky spools of dispersion compensating fiber (DCF) at each in-line amplifier site and major modifications of the design of in-line amplifiers to accommodate the loss of the DCF. Even though these changes required forklift upgrades of installed systems and a new approach to the network planning, the result was better and -very important! - less expensive networks. For example, increasing ETDM rates by a factor of four historically reduced the equipment cost for the transmission of a unit bandwidth by a factor of two (in addition to the savings in operation cost such as network management and power consumption). Extrapolating the historical evolution of ETDM rates of commercially deployed systems, and taking into account that 10Gb/s systems started to be deployed in 1995-1996, one can expect to see deployment of 40Gb/s systems in 2002-2003. In this paper, we will discuss the following question: what will it take for the carriers to introduce the 40Gb/s technology in their fiber-optic networks? Does this transition require major changes in the networks, similar to the previous technological changes? This question is especially important in the current economic situation where service providers are cutting their capital expenses since major changes require major capital spending. As it will be shown in the paper, ***from the carrier's perspective, the transition to 40Gb/s systems is expected to be painless and trivial in comparison with the previous technological changes.***

Figure 1 shows a schematic diagram of a typical dense WDM optical communication system employing an ETDM rate of 10Gb/s rate per optical WDM channel. Each transponder transmits and receives a 10Gb/s optical signal at a specific wavelength

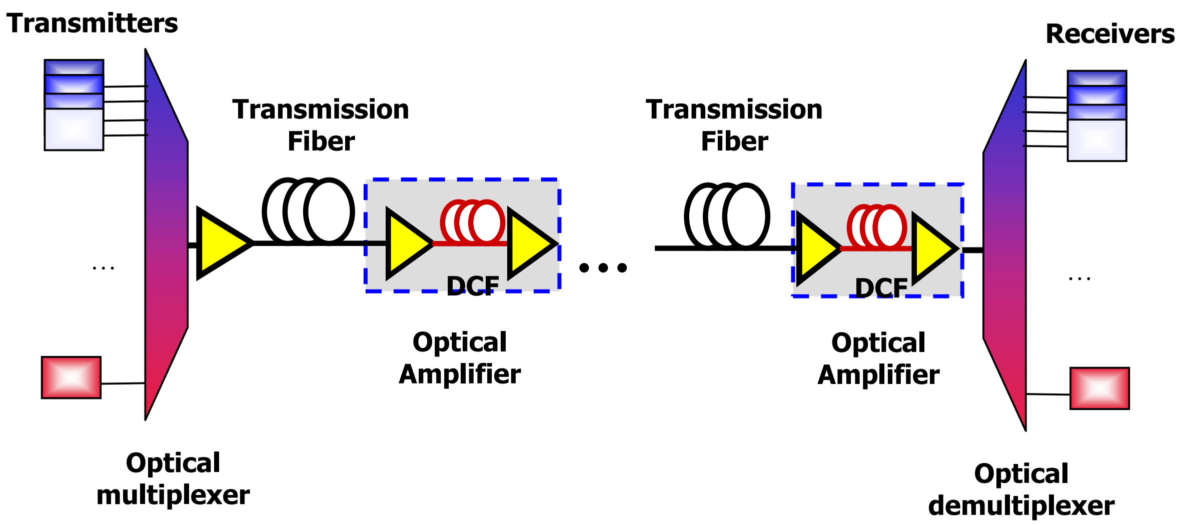

Figure 1. *Schematic diagram of a typical WDM 10Gb/s system. 40Gb/s transmission can be done over that system just by replacing 10Gb/s transponders by 40Gb/s ones (see text).*

corresponding to that WDM channel. At the transmitter side, 10Gb/s optical signals from different WDM channels are first optically multiplexed by an optical WDM multiplexer. The WDM signal is then sent to a transmission fiber link. To compensate for the loss of the fiber, optical amplifiers (in most cases, these are Erbium-doped fiber amplifiers (EDFA), in some cases it is Raman-assisted EDFAs, and in some cases it could be pure Raman amplifiers) are installed after each span; a typical span length is 60-120 km. Also, to compensate for the chromatic dispersion of the transmission fiber, dispersion compensating fiber spools (also called dispersion compensating modules, DCM) are installed in between the stages of the in-line optical amplifiers. After transmission through the link, the WDM signal is optically demultiplexed and each WDM channel is detected by the receiver part of a corresponding transponder. It is important to emphasize that during the previous technological transition from 2.5Gb/s to 10Gb/s ETDM rates, in addition to the obvious replacement of 2.5 Gb/s transponders by 10Gb/s ones, all the major parts of the optical transmission line had to be replaced (like optical amplifiers, multiplexers and demultiplexers) or even totally newly introduced (dispersion compensation fiber). Surprisingly enough, none of these parts will have to be replaced in order to migrate from 10Gb/s to 40Gb/s systems. Below we consider the technological advances that make this transition so simple for the carriers.

The following factors may introduce impairments to an optical signal when it is being transmitted through a transmission line: the fiber chromatic and polarization mode dispersion, fiber nonlinearity, spontaneous emission noise from the optical amplifiers and spectral filtering by optical multiplexers/demultiplexers.

When operating at high data rate such as 40Gb/s, chromatic dispersion of the transmission fiber quickly broadens the optical data pulses. The dispersion tolerance of 40Gb/s transmission is roughly ±50ps/nm which corresponds to only 3km of standard single-mode fiber. This fact leads to the very popular misconception that dispersion is prohibitive to long-haul 40Gb/s transmission. The truth is that dispersion is very useful to combat the fiber nonlinearities when used together with the periodical dispersion compensation. This approach of periodical dispersion compensation with DCF is already being used in 10Gb/s systems (see figure 1). The real challenge for 40Gb/s transmission in comparison with 10Gb/s systems is the requirement on the accuracy of the dispersion compensation at the output of the transmission link: the dispersion tolerance of 40Gb/s transmission is 16 times tighter than that of the 10Gb/s and 256 times tighter than that of 2.5Gb/s! Granularity of dispersion values of commercial DCM is good enough for 10Gb/s systems but certainly not enough for 40Gb/s. Also, since we are considering not just a single-channel transmission but multi-channel WDM transmission, one has to make sure that dispersion is properly compensated at all wavelengths corresponding to the WDM channels. Unfortunately, this is not easy: the dispersion of the transmission fiber and of the dispersion compensation fiber changes with wavelength, the so-called dispersion slope. Modern fiber technology makes it possible to produce DCMs that compensate both the transmission fiber dispersion and the dispersion slope, i.e. compensate the transmission fiber dispersion at all wavelengths of interest. However, DCM manufacturing tolerances as well as uncertainties in the parameters of the transmission fiber itself make dispersion compensation with only fixed DCMs in practical 40Gb/s long haul WDM systems difficult. Moreover, another problem exists. The fiber dispersion is slightly temperature dependent. In ultra-long transmission (greater than 1000 km), especially if the transmission fiber is not buried in the ground, outside temperature variations (winter-summer, day-night) may cause dispersion variations of the fiber transmission link which are too high for 40Gb/s. Fortunately, the state-of-the-art technology offers a very simple yet effective solution to all the above-mentioned problems: the adaptive dispersion compensator. The adaptive dispersion compensator (A-DCM) is a relatively inexpensive and very compact device with the size of a pen, see figure 2. It is placed in each transponder in front of the receiver.

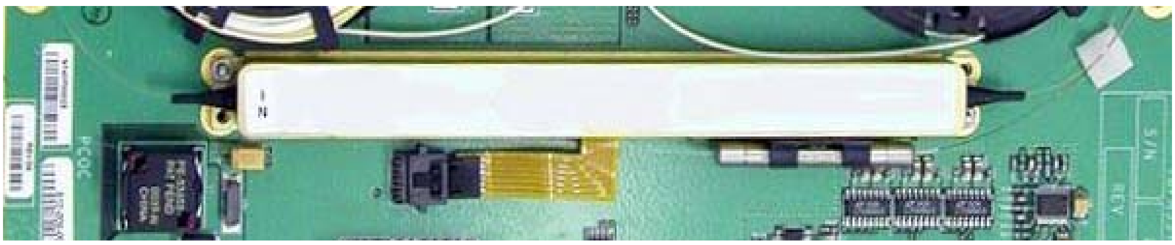

Figure 2. *Adaptive dispersion compensator is a compact device sitting on the receiver board in each 40Gb/s transponder.*

Figure 3 illustrates the drastic improvement in the dispersion tolerance of a 43Gb/s receiver when an A-DCM is used. The figure shows optical signal to noise ratio (OSNR) penalties at a bit error rate of 10^{-15} for the cases with and without A-DCM as a function of how much the total link dispersion deviates from the optimum value.

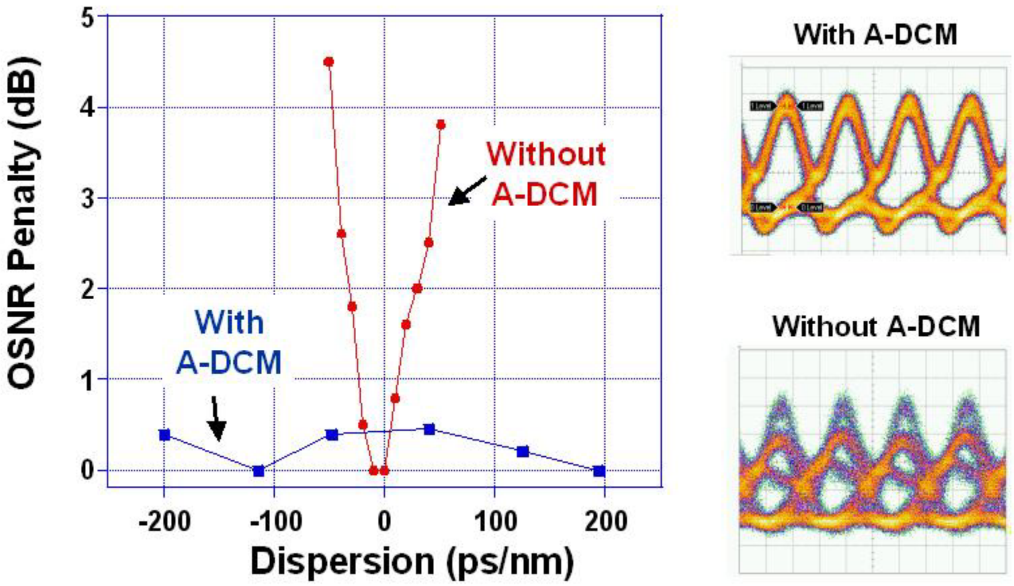

Figure 3. *Penalty for a 43Gb/s signal transmission as a function of deviation of the total link dispersion from the optimum value. The two curves compare the situation with and without adaptive dispersion compensator (A-DCM). One can see a drastic improvement in the dispersion tolerance when A-DCM is used. Corresponding eye diagrams are shown on the right for the case of a total link dispersion deviating –50ps/nm from the optimum value.*

As one can see, without the A-DCM the tolerable range of total link dispersion is low and the penalty increases very quickly when total link dispersion deviates from the optimum. When the A-DCM is implemented in the receiver, the penalty is almost negligible within a wide range of total link dispersion. The eye diagrams in figure 3 further illustrate the comparison: when the total link dispersion deviates –50ps/nm from the optimum value, the eye diagram is severely distorted due to the intersymbol interference caused by the dispersion-induced pulse broadening if the A-DCM is not used. However, using an A-DCM, the eye can be restored almost perfectly. As a result of the A-DCM implementation into the 40Gb/s transponders, the dispersion tolerance of 40Gb/s transponders becomes essentially the same as that of 10Gb/s transponders. ***This means that 40Gb/s systems do not require new in-line dispersion compensation modules: the same DCMs, with the same granularity and tolerances on dispersion and dispersion slope, which are currently being used in 10Gb/s systems, can be used in 40Gb/s systems.***

Similar to the case of lower bit rate transmission, fiber nonlinearities may become detrimental when transmitting 40Gb/s WDM signals over long distances. As we have mentioned above, transmission fiber dispersion together with periodical dispersion compensation by DCMs, counteracts to the detrimental effect of the nonlinearity. Specific combinations of the fiber dispersion and the dispersion of DCMs (so-called dispersion maps) can tremendously reduce the nonlinear penalties even after transmission over thousands of kilometers. Note that the dispersion map optimization is already known from the design of 10Gb/s systems. As it has been shown in our extensive simulations and many experimental tests, the optimal dispersion maps for 40Gb/s transmission are very forgiving and can be easily implemented in the field with any type of commercial fiber using standard DCMs currently being used in 10Gb/s systems. Moreover, ***40Gb/s signals can be successfully transmitted over transmission links designed and optimized for 10Gb/s transmission.*** Advanced modulation formats of the optical signal can further reduce the nonlinear penalties. Carrier-suppressed return-to-zero modulation format (CS-RZ) improves robustness of 40Gb/s transmission not only with respect to the fiber nonlinearities but also with respect to spectral filtering and polarization mode dispersion. ***40Gb/s CSRZ signals transmit with a minimal penalty through the standard 100GHz-spaced optical multiplexers and demultiplexers designed for and being used in 10Gb/s systems.***

Polarization mode dispersion (PMD) is a factor that for certain long routes must be taken into account. PMD in fibers is caused by imperfection of rotational symmetry around the fiber axis which leads to a slight fiber birefringence. The fiber birefringence leads to a dependence of the signal speed on the state of its polarization and thereby to broadening of the transmitted pulses and the risk of intersymbol interference. Since 40Gb/s transmission is four times more sensitive to PMD than 10Gb/s, it is natural to ask if PMD is a serious obstacle to deploying 40Gb/s systems? In most cases the answer is “no” as the following discussion will show. PMD-induced penalty becomes significant when the pulse broadening becomes comparable with the bit duration corresponding to 23 ps for a 43Gb/s signal. Normally, the PMD-induced penalty is considered to be acceptable if it is less than 1 dB. This penalty of 1dB will arise for return-to-zero modulation formats if the PMD of the transmission line introduces about 10ps of instantaneous differential group delay (DGD) between the fastest and the slowest polarization state. The acceptable amount of DGD is somewhat lower for the traditional non-return-to-zero (NRZ) format. Based on the acceptable amount of DGD, one can easily calculate the maximum allowable PMD value of the transmission fiber as a function of the distance for links without PMD compensation. The result is shown in figure 4. The red curve in figure 4 takes into account the PMD of both the transmission fiber and the in-line

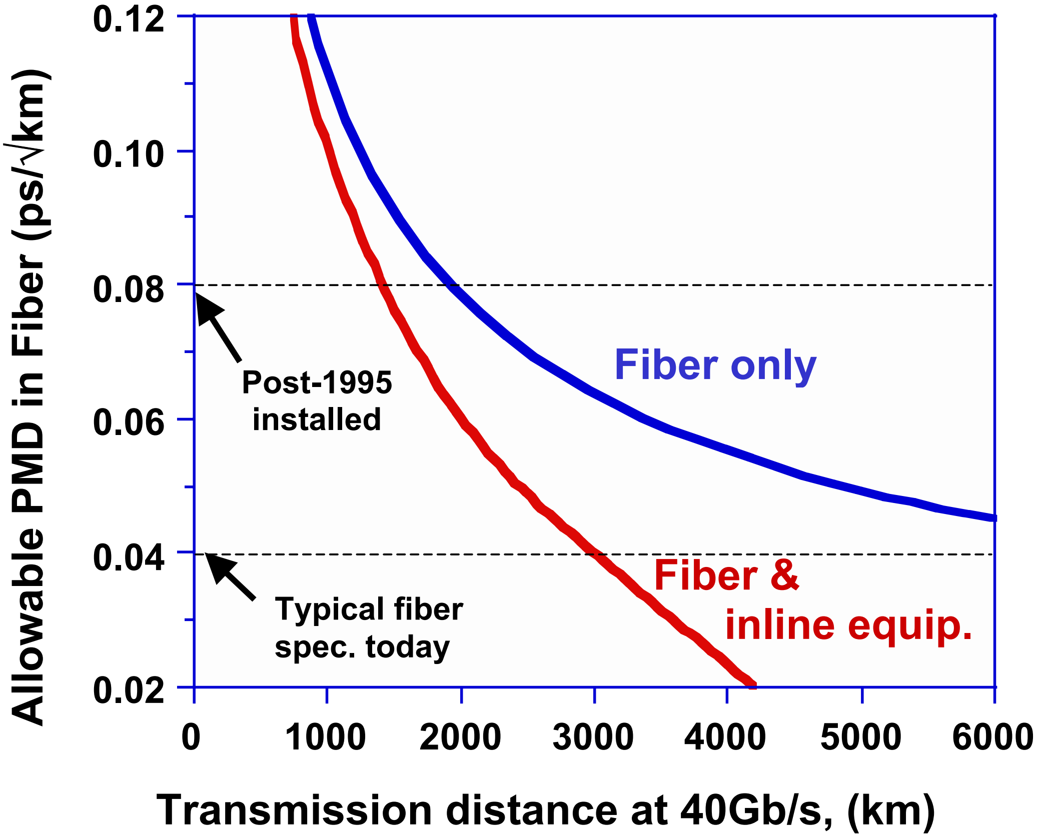

Figure 4. *Allowable fiber PMD as a function of the 40Gb/s transmission link distance. Blue curve – only the PMD of the fiber is taken into account. Red curve – the PMD of both the fiber and the in-line equipment is taken into account. With the currently available in-line optical amplifiers and DCMs, PMD is not a problem for 40Gb/s transmission up to more than 1,000km of a vast majority of post-1995 fiber (red curve). With the fiber currently being installed this distance increases to more than 3,000km.*

equipment (optical amplifiers, DCMs etc) assuming typical current PMD specifications for this equipment. The blue curve takes only the PMD of the transmission fiber into account – that may describe a future situation when the PMD parameters of the in-line equipment will be greatly improved. Figure 4 also indicates that the vast majority of the fiber installed after 1994-1995 has a PMD value less than 0.08 - 0.1ps/√km, and the PMD specifications on the fiber which is currently being produced and installed is less than 0.04ps/√km. (It is interesting to note that KDDI reported at the National Fiber Optic Engineering Conference in Dallas this year that the average PMD of their fiber deployed in recent years was as low as 0.03ps/√km). As one can see from the figure 4, ***with the currently available in-line optical amplifiers and DCMs, PMD is not a problem for 40Gb/s transmission up to more than 1,000km of a vast majority of post-1995 fiber, and with the fiber currently being installed this distance increases to more than 3,000km.*** With the future improvements of PMD specifications of the in-line equipment, these distances increase to 1,400-2,000km for the post-1995 fiber and to more than 7,000km for the fiber currently being installed. In this connection, it is also worth to mention that most of the routes in terrestrial systems are shorter than 500km. Finally, it should be mentioned that PMD values were not specified for fiber installed prior to 1994-1995, and that this old fiber sometimes has high PMD. If one wants to run 40Gb/s over this high-PMD fiber, PMD compensators must be used. Different types of commercial PMD compensators are emerging to the market.

As in the transmission at lower data rates, the maximum transmission distance of 40Gb/s systems is constrained by the fiber nonlinearities that set the upper limit on the launch optical power and by the spontaneous emission noise from the in-line optical amplifiers which sets the lower limit on the signal launch power in order to meet the required optical signal to noise ratio at the transmission output. ***There are no special requirements for the optical amplifiers to be used in 40Gb/s systems***. Amplifiers, which are currently being used in 2.5Gb/s and 10Gb/s WDM systems, can very well be used in 40Gb/s systems. Despite a popular misconception, ***Raman amplifiers are not imperative for 40Gb/s transmission***: any type of amplifiers - EDFA, hybrid Raman/EDFA or pure Raman amplifiers - can be used. We have demonstrated long-haul WDM 40Gb/s transmission at 100GHz channel spacing over distances from 700km to more than 5,000km using all these types of amplifiers.

Since Raman amplifiers have a better noise performance than EDFA, transmission distances are higher with the Raman amplifiers. However, commercial 40Gb/s WDM systems longer than 500km with large margins can be made today even without using Raman amplifiers, while Raman systems can now be longer than 1,000km. These numbers are for the commercial non-Raman and Raman amplifiers that are currently being used in lower data rate systems. These numbers keep improving with time.

Summarizing, one can conclude that the transition to 40Gb/s systems will be trivial for the carriers. 40Gb/s systems can use the same transmission links as 10Gb/s systems use now: same transmission fiber, same optical multiplexers and demultiplexers, same optical amplifiers and in-line dispersion compensators. One can even mix 10Gb/s and 40Gb/s WDM channels in one system. That approach is very attractive for the network design. Also, carriers can save expenses by adding 40Gb/s waves to the existing 10Gb/s WDM systems. By doing this, they can also keep increasing capacity of existing systems and thus postponing the necessity of installation of new systems. As in previous technological transitions to the higher ETDM data rates, 40Gb/s technology offers higher capacity and more economical networks. With the current technological advances, bringing 40Gb/s systems into the optical networks should also be seamless and painless.

