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Engaging Electronic Engineering Students in Realistic Engineering Problems: Calculations on the Feasibility and Implementation of Optical Communication Links

Review Article

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Abstract

The article describes a task on the feasibility and possible options regarding the implementation of actual optical communication links. The task regards three (3) fiber-optic links with different transmission lengths and bit-rates and the students have to decide on the feasibility and implementation options for those links. The task is formulated in a problem-solving manner (in the sense that it refers to actual situations, more than one options may be considered feasible while some solutions may lead to revisiting initial calculations on the basis of new data). The basic aim of the task is the students to work on issues that most probably will encounter during their professional life and, at the same time, develop a conceptual understanding and a working knowledge on a broad range of essential concepts and notions regarding optical communication links.

Keywords: Engineering education; Electronic engineering education; Fiber optics; Optical communications

Abbreviations: CD: Chromatic Dispersion; PMD: Polarization-Mode Dispersion; ITU: International Telecommunication Union; BER: Bit-Error Rate; OSNR: Optical Signal-to-Noise-Ratio; DCF: Dispersion Compensation Fiber; WDM: Wavelength-Division Multiplexing; DWDM: Dense Wavelength-Division Multiplexing; CWDM: Coase Wavelength-Division Multiplexing; FTTH: Fiber to the Home.

Introduction

It has been observed that students, even those familiar with the essentials of signal impairment mechanisms, find it difficult to combine the various pieces of their knowledge and come to a proper decision regarding the feasibility and the features of a specific telecom link.

Given the above, the article describes a task on the feasibility and the possible options regarding implementation of actual point-to-point fiber links. The basic parameters of the fiber links (such as length and bit-rate) have been carefully chosen so as to allow a broad range of possible solutions. The task is given in a problem-solving manner in the sense that (i) it refers to actual situations, (ii) there is no single solution path since alternative options may be proposed and (iii) some solutions may lead to revisiting the initial calculations on the basis of new data. The basic aim is the students to show initiative and, through the investigation of the practical aspects of actual telecommunication links, to develop a conceptual and operational understanding of previously acquired knowledge and possibly discover a new one. Finally, the students can combine knowledge for each separate transmission impairment in order to solve a problem with all impairments taken into account thus enhancing their synthetic thinking.

As in actual fiber links, students will have to make calculations on transmission parameters such as signal's attenuation, chromatic dispersion (CD) and polarization-mode dispersion (PMD). Regarding dispersion, calculations will be performed from the receiver's tolerance perspective and taking into account that the commonly used types of fiber cables contain either standard (G.652) fibers or non-zero dispersion-shifted (G.655) ones [1,2]. This perspective goes beyond the conventional approach which evaluates the bit-rate/length product on the basis on the CD coefficient and the transmitter's spectral width.

The task is to be included (as a separate module) in the "Optical Communications" compulsory course and the "Photonics & Telecommunications" optional course offered at the 6th and the 9th semester of the Dept. of the Electrical & Electronics Engineering Dept., School of Pedagogical & Technological Education (ASPETE), Athens, Greece.

Methodology

The basic aim of the task is the students to use previously acquired knowledge in order to make decisions regarding actual telecommunication applications, in this case specific fiber-optic links. It is considered important the students to work on different link types and identify possible merits and drawbacks of each solution.

Some of the concepts and issues that the students will have to take into account, in order to propose appropriate solutions for the fiber links under study, are the following:

- The main types of fiber cables to be used (as described in the G.652 and G.655 recommendations of the International Telecommunication Union - ITU) and their basic features.
- Basic parameters of optical transmitters and receivers (such as the wavelength of operation and the transmitted power of a laser transmitter and the sensitivity of an optical receiver).
- The attenuation margin of a fiber link (depending on the features of transmitters and receivers mentioned above) as well as the attenuation coefficient regarding main fiber types (e.g. the G.652 and G.655 fiber cables).
- Transmission impairments due to the CD and PMD and their dependence on the bit-rate.
- The receiver's tolerance regarding CD and PMD on the basis of the OSNR-penalty notion and the involved notions of bit-error rate (BER) and quality factor Q.
- The use of dispersion compensation fibers or regenerators and the associate implications on the original link.
- The possible use of Erbium-doped fiber amplifiers (EDFAs) and its association with issues like power budgeting and the wavelength of operation.
- The possible use of wavelength-division multiplexing (WDM) (as opposed to a single-wavelength solution) and the choice of the appropriate WDM technique (coarse or dense).
- The students will be asked to decide on the feasibility and the implementation options regarding the following links:
- Link 1: A 50 km link with a bit-rate of about 2,5 Gb/s and an estimated annual increase about 5%.
- Link 2: A 100 km link with a bit-rate of about 6 Gb/s and an estimated annual increase about 5%.
- Link 3: A 200 km link with a bit-rate of about 10 Gb/s and an estimated annual increase of 5%.

Before starting their work, the students will be provided with selected literature (e.g. [3-6]) on the issues relevant to the given task. In order the students to develop a broader perspective on the subject (and, at the same time get accustomed to using multiple sources of information) the literature will be in addition to the course's textbook (which will be used, anyway, regarding fiber-optic essentials).

General Remarks

The decision on the feasibility of a fiber-optic link is primarily based on calculations regarding attenuation (that is, power budgeting) CD and polarization-mode dispersion (PMD) [3,7].

Regarding attenuation (and given that a typical laser transmitter has an output power of about 1 mW while a typical receiver has a sensitivity of about 1 μW) a basic fact is that fiber links have an attenuation margin of about 30 dB. Allowing for a link degradation (due to cable ageing, accidental cuts etc.) of about 5–10 dB, it is concluded that the usable attenuation margin is about 20–25 dB. Another basic fact is that a typical fiber cable (whether G.652 or G.655 type) has an attenuation coefficient of about 0.4 dB/km at 1310 nm and about 0.2 dB at 1550 nm. Thus, by using the equation:

$$A = a_f L_A + C \qquad (1)$$

(where A is the attenuation margin in dB, a_f is the attenuation coefficient in dB/km, and C is the cable degradation in dB), one can calculate the maximum amplifier-free length L_A (in km).

Another consideration would be the expandability of the link. For example, link 1 will start with initial bit rate $R_{1,i}$ = 2.5 Gb/s but, given the estimated annual increase in telecom traffic and the fact that the typical life of such a link is about 25 years, it may reach a bit rate of about $R_{1,f}$ = 8.5 Gb/s. That means that the decision will be either a single-wavelength link of 10 Gb/s or a WDM one to be expanded from a 1x2.5 Gb/s to a 4x2.5 Gb/s capacity depending on the actual bit-rate increase [6].

Regarding dispersion (either CD or PMD) the receiver's tolerance has to be taken into account. For example, the receiver's tolerance on CD, at a bit-rate of 2.5 Gb/s and for a 1 dB penalty in the optical signal-to-noise-ratio (OSNR), is about 12800 ps/nm [4,7]. However, as the bit-rate increases, the dispersion tolerance is reduced in a square-law manner (for example, at a 10 Gb/s bit rate, the CD tolerance will be about 16 times lower, that is 800 ps/nm). The above figures have to be associated with the CD coefficient of the fiber cable to be used which, at a 1550 nm wavelength, is about 17 ps/nm.km for a G.652 cable and about 5 ps/nm.km for a G.655 one. Thus, by using the equation

$$T_{CD} = D_{CD} L_{CD} \qquad (2)$$

(Where T_{CD} is the receiver tolerance to chromatic dispersion in ps/nm and D_{CD} is the fiber's dispersion coefficient in ps/nm.km), one can calculate the maximum compensation-free length L_{CD} (in km).

Regarding PMD, the receiver's tolerance at a bit-rate of 2.5 Gb/s, for a 1 dB penalty in the OSNR, is about 40 ps and is reduced in a proportional-like manner as the bit-rate increases (for example, at a 10 Gb/s bit rate, the PMD tolerance will be about 4 times lower, that is 10 ps). The above figures have to be associated with the PMD coefficient of the fiber cable to be used which is usually from 0.1 ps/ √km to 0.5 ps/√km[8]. Thus, by using the equation

$$T_{PMD} = D_{PMD} \sqrt{L_{PMD}} \qquad (3)$$

Where T_{PMD} is the receiver tolerance to chromatic dispersion in ps and DPMD is the fiber's PMD coefficient in ps/), one can calculate the maximum compensation-free length L_{PMD} (in km). The values of L_A, L_{CD} and L_{PMD} will dictate whether and where (along the link) amplifiers and/or dispersion compensation fibers or regenerators have to be installed.

The financial parameter will be also taken into account though detailed considerations are beyond the scope of the described task. However, the students will have to note that G.655 cables may be a bit more expensive than the conventional G.652 ones and that as far as the terminal equipment is concerned, the 1550-nm technology may be more expensive than the 1310-nm one. Finally, students will be asked to comment on the BER testing of the above links mainly regarding the measurement arrangements as well as its possible duration for an intended BER of 10^{-9} [3,9].

Link 1

Regarding link 1 (length L = 50 km, initial bit-rate $R_{1,i}$ = 2.5 Gb/s, final bit-rate $R_{1,f}$ = 8.5 Gb/s) the students are expected to choose the 1310 nm technology since for a link 50 km long, EDFAs will not be necessary (eq. (1) yields that the amplifier-free distance is well over the length of the link). Regarding choice between a single-wavelength link of 10 Gb/s and an expandable coarse WDM (CDWM) link, one has to think that the single-wavelength link avoids the cost of the CWDM equipment but, at the same time, it includes the higher cost of the 10 Gb/s transmitter. On the other hand, a CWDM solution has the advantage of a reduced initial cost since a single 2.5 Gb/s link is initially needed. In either case, eqs (2) and (3) suggest that the compensation-free length is larger than the length of the link, hence dispersion compensation will not be needed (Figure 1).

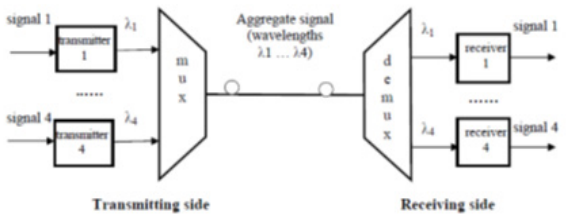

Figure 1: Schematic of the CDWM solution for link 1 (for the sake of simplicity, only one communication direction is depicted).

Link 2

Regarding link 2 (length L = 100 km, initial bit-rate $R_{2,i}$ = 6 Gb/s, final bit-rate $R_{2,f}$ = 20.3 Gb/s) a choice has to be made between a single-wavelength link (of a 40 Gb/s bit-rate) and a DWDM 3x10 Gb/s link with the preferable option mainly dictated by receiver's tolerance towards CD. Indeed, as obtained by eq. (2) and given that for a 40 Gb/s bit-rate, the receiver's tolerance is about 50 ps/nm √km , the maximum distance without dispersion compensation on a G.655 fiber cable (with a CD coefficient of 5 ps/nm.km) will be about 10 km (too short compared with the link's length of 100 km). On the other hand, the use of a 10 Gb/s bit-rate will allow for a CD-free distance of 160 km which is well above the link's length.

However, for a bit-rate of 10 Gb/s, PMD must be also taken into account. Given that, at this bit-rate, the receiver tolerance is 10 ps, even on a cable with a PMD coefficient of 0.5 ps/ (worst-case value), the compensation-free distance (as obtained by eq. 3), is 400 km much larger than the link's length. As far as the operating wavelength is concerned, the choice of 1550 nm is dictated, among others, by the need for the lowest possible attenuation coefficient to cover the whole length of the link. Indeed, with an attenuation coefficient of 0.2 dB/km (at 1550 nm) eq (1) suggests that the amplifier-free distance even in the worst-case scenario (fiber degradation accounted to 10 dB) is about 100 km (equal to the length of the link). In any case, the use of the 1550 nm wavelength allows for the possible use of an EDFA should that be considered necessary. The proposed solution is illustrated in Figure 2.

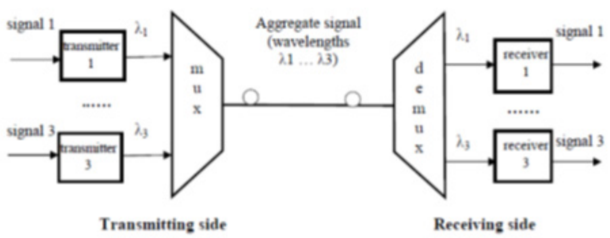

Figure 2: Schematic of the proposed solution for link 2 (for the sake of simplicity, only one communication direction is depicted).

Link 3

Regarding link 3 (length L = 200 km, initial bit-rate $R_{3,i}$ = 10 Gb/s, final bit-rate $R_{3,f}$ = 34.9 Gb/s) the amplifier-free distance is between 125 and 100 km (depending on the evaluation of the fiber degradation which may be from 5 and 10 dB). Given that the fiber link is 200 km, one or two EDFAs have to be employed which makes of the 1550 nm wavelength the only available option. Regarding choice between a single-wavelength link (of a 40 Gb/s bit-rate) and a DWDM 4x10 Gb/s one, the preferable solution will again be dictated by the receiver's tolerance towards CD. As in link 2, at a 40 Gb/s bit-rate, the compensation-free distance is about 10 km while in a 10 Gb/s, it can be 160 km.

Given the link's length (200 km) a dispersion compensation mechanism has to be employed. This can be either a dispersion compensation fiber (DCF) or a signal regenerator. However, the use of regenerators will not be preferred since a separate regenerator will be used for each multiplexed wavelength increasing in this way the overall operational costs. On the other hand, the use of a DCF will increase the length of the link (typically 1 km of DCF is used per 20 km of the original fiber) which means that power budgeting has to be revised. As in link 2, the PMD does not affect the link since the compensation-free distance of 400 km (cable with a PMD coefficient of 0.5 ps/ √km) is much larger than the link's length. The proposed solution is illustrated in Figure 3.

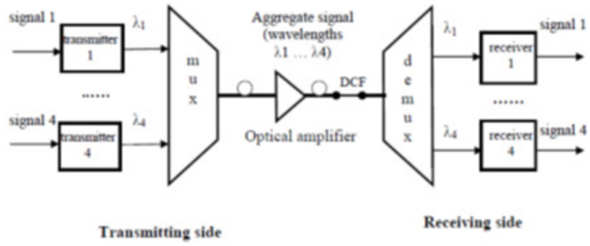

Figure 3: Schematic of the proposed solution for link 3 (for the sake of simplicity, only one communication direction is depicted).

Discussion

Though the described task will be included in the relevant courses from the next (2022-23) academic year, it is expected that it will be well received by the classes involved. This stems from discussions made with the students as well as their reception of respective (though smaller-scale) tasks given in other telecommunication courses. This is congruent with the fact that students usually prefer to work on practical rather than theoretical issues and are happy to get involved in actual applications that might encounter in their professional life.

It is considered important that the students show initiative, discuss and exchange ideas and validate their thoughts. The instructor will guide and assist them in their work but he/she will not provide them with ready-made solutions. Depending on the teaching time available and the experience obtained, the described task could be extended to include listing of the necessary modules and materials together with their basic technical characteristics.

Another possibility could be the formulation of a task that could refer to access networks and fiber-to-the home (FTTH) applications. Due to their short lengths, such networks are usually not susceptible to attenuation and dispersion however they may present attenuation limitations if power splitting is applied. Such a task would be more suitable for the "Photonics and Telecommunication" course which deals with more advanced and state-of-the art issues than the "Optical Communications" one. An additional task could regard optical wireless links given the intensifying interest for this type of communication. Both tasks could be combined with students encountering various state-of-the-art issues of optoelectronic research improving their grasp of the optical communication subject.

Conclusion

The basic aim of the proposed task is the students to encounter actual fiber-optic applications and, through a problem-solving procedure (with open issues and multiple options) associate theory with practice thus enhancing their knowledge and conceptual understanding. Given the fact that most engineering students would be happy to work on actual applications as similar as possible with situations that may encounter as professional engineers, it is expected that the task will be well received and enhance students' motivation and active involvement in the learning procedure.

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At the more advanced level of the "Photonics and Telecommunication" course, additional tasks could be formulated to cover applications on state-of-the-art topics such as FTTH networks and wireless optical links.

Conflict of Interests

The authors declare no conflict of interests.

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