Duplexing methods for PON systems using multimode fiber with multicarrier transmission

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Deploying a PON using multimode fiber in the access network is viewed as a cost-effective solution. However, a multimode fiber link exhibits a time-dispersive nature. To cope with this problem, an OFDM transmission method is used. In this work, a comparison study on several duplexing methods for this system was performed to decide upon the recommended method for the system. The choices that were examined are: TDD, FDD, WDD and SDD (time-, frequency-, wavelength- and space- division duplexing). Based on the following criteria: channel characterization, flexible bandwidth proportion, crosstalk & beat noise impairment, components-saving and system capacity, it was concluded that SDD is the most feasible one among other choices, immediately followed by WDD.

Introduction

After quite successful developments in increasing the network capacity of long-haul/core networks with optical technologies, the development focus has shifted to the access networks which are still the major bottlenecks for broadband access. This has sparked developments of xDSL technologies, along with coax data network technologies and broadband wireless technologies. However, it has been a consensus that a FTTH system (with PON as a main form) is the most future-proof and potentially feasible solution, because it can support adequate throughput and distance at the same time. But until now, large investments are still problematic for the deployment of PON systems. This is especially true for PON systems using single-mode optical fiber because of its high installation costs. In this respect, the use of multimode fiber for PON systems may help reduce the installation and maintenance costs, hence the overall deployment costs, as it is relatively easier to handle (e.g., connecting, coupling, splicing, etc.) multimode fiber compared to single-mode fiber.

The expected deployment reach of PON systems considered in this paper is up to 5 km. In this case, the effect of chromatic dispersion can be neglected (provided suitable optical wavelengths and relatively narrowband light sources are chosen). Nevertheless, intermodal dispersion restricts the bandwidth-distance product of a common multimode fiber below 1 GHz·km for baseband transmission. This value of bandwidth-distance product is too small for broadband access (with shared capacity of Gbps order). To overcome this limitation, the use of passband transmission using higher-order transmission lobes of the multimode fiber is proposed [1]. By this scheme, it has been shown in [2] and other papers that the limitation above can be overcome.

Time-dispersive nature and multicarrier transmission

In the electrical domain (after optical detection), passband transmission through multimode fiber encounters a phenomenon which is similar to multipath fading in wireless systems, due to the time-dispersive nature of multimode fiber. The time-dispersive nature is the consequence of the intermodal dispersion as each mode has unique modal delay. These modal delays can be considered statistically distributed [3], especially if one considers the optical signal propagation from end-to-end which covers several stages of connectors, couplers, fiber strands, etc. The launching condition, the installation condition (especially at the customer premise) and the environmental condition also affect the propagation of each mode, hence also the modal delays. It should be noted that the latter may render the system state time-dependent.

Because of multipath fading, broadband RF signals will be distorted at the receiver unless some measures are taken. One promising solution is to use multicarrier transmission. This technique is to be used for the PON system described in this paper. The basic idea is that the original bitstream is split into parallel bitstreams where each parallel bitstream modulates a subcarrier (with a unique frequency). The symbol time of each modulated subcarrier becomes longer accordingly. By this virtue, each modulated subcarrier now has smaller bandwidth such that each one only experiences flat fading. The superposition of these modulated subcarriers subsequently modulates the optical carrier. At the receiver side, the reverse operation is done to recover to the original bitstream. With the advance of DSP technology, the main form of multicarrier transmission is Orthogonal Frequency Division Multiplexing (OFDM), based on FFT/IFFT operations [4]. The key difference between multicarrier and ordinary subcarrier transmission is that for the former case, each node in general can use several subcarriers simultaneously for transmission.

Duplexing methods

As a part of the system definition, the duplexing method to be used must be determined. Duplexing itself is a mechanism to coordinate parallel transmission and reception for a pair of nodes where bidirectional communication takes place. In the case of a PON, it is between the OLT and an ONU/ONT, where transmission from OLT to ONU/ONT is termed downstream, and the reverse is upstream. Four duplexing methods are examined in this paper: FDD, TDD, WDD and SDD. The last two are typical duplexing methods for optical networks (two fiber strands are used in case of SDD), while FDD and TDD are the alternative duplexing methods when a single optical wavelength and a single fiber strand are to be used. The important point to note here is that these four duplexing

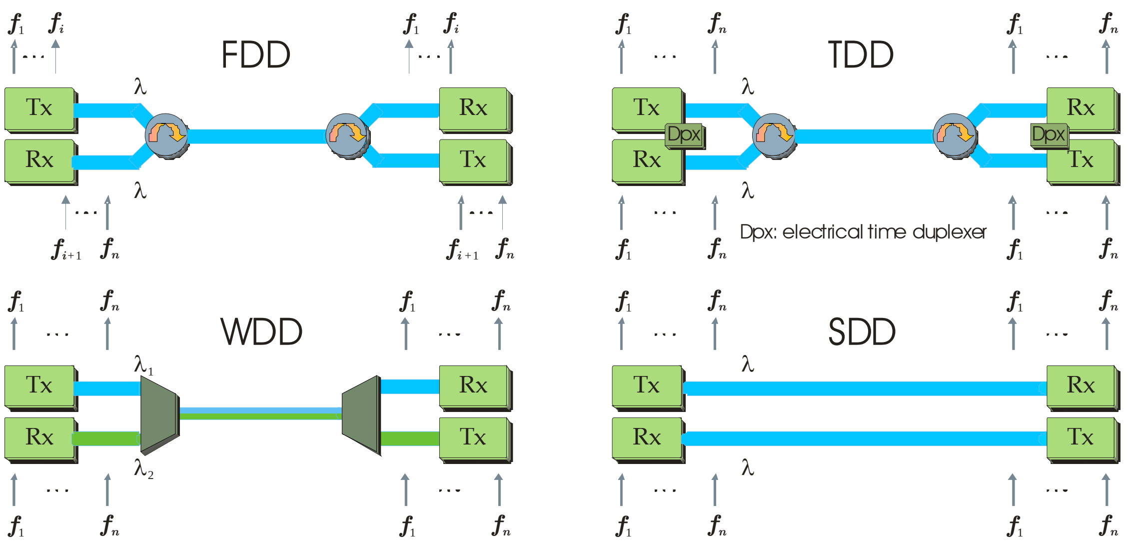

Figure 1: Duplexing methods under evaluation

methods are analyzed with respect to a system using multicarrier transmission.

Channel characterization: To improve the performance for systems using multicarrier transmission, channel characterization is used to estimate the quality of each subchannel (a frequency band defined by each subcarrier). The idea is to use higher-order modulation for subchannels with good quality (high SNR) and vice versa. This way, the system throughput can be increased. Adapted from wireless systems, the first impression may be that the use of TDD has a clear advantage because the characterization can be done either by upstream or downstream only. This is because the channel is assumed to be reciprocal. But it turns out that in PON case using multimode fiber with multicarrrier transmission, this assumption is in general unattainable. This is because it is difficult to control the propagating modes such that they are identical for upstream and downstream even when a single fiber strand and a single wavelength are used. With this fact, TDD scheme, along with FDD, WDD and SDD schemes, requires bidirectional channel characterization anyway.

Flexible bandwidth proportion: Because the upstream time interval and downstream time interval for TDD in general can be changed, it's straightforward to see that the bandwidth proportion between upstream and downstream transmissions in TDD scheme can be made flexible. Indeed, this is an inherent advantage of TDD, especially with respect to dynamic bandwidth demands for upstream and downstream of nowadays data-dominated traffic. Unlike in wireless systems and ordinary subcarrier-multiplexed systems, due to multicarrier transmission, it's quite natural for a FDD scheme to distribute subchannels (which have small capacity individually) dynamically for upstream and downstream transmission such that a flexible bandwidth proportion can be achieved. It should be noted that this dynamic distribution is coupled tightly with the multiple access mechanism.

The WDD and SDD schemes can also use the aforementioned way to achieve flexible bandwidth proportion if multicarrier transmission is used. The conclusion for this consideration is that all duplexing schemes can support flexible bandwidth proportion with TDD scheme has a small more advantage as TDD scheme usually can achieve finer proportion.

Crosstalk & beat noise impairment: Typically, optical circulators are used for optical networks using a single fiber strand and a single optical wavelength for both upstream and downstream transmissions (i.e., the FDD and TDD cases). For optical circulators, one relevant thing to be cautious about is the optical signal leakage from port 1 to port 3 (i.e., from light source to photodetector). A typical value for this leakage (characterized as directivity) is 40 dB. Potentially serious crosstalk may result especially if the system operates on a tight power budget (the use of optical amplifiers is not considered in this paper). In this case, the received signal and the leakage signal may be of similar order of magnitude. From this situation, beat noise also exists as the received and the leakage signals mix at the receiver [5]. However, in short range application like access networks, the received signal can be several orders stronger than the leakage signal; hence, the use of single fiber strand and single wavelength is possible. This consideration also applies for similar problem caused by backreflection. Nevertheless, the use of FDD has to deal with this potential problem which translates easily into a penalty in power budget.

By TDD, the impact of this problem can be much reduced because transmission and reception occur at different time interval. This means that the receiver can ignore any leakage signal. For the back-reflected signal, it is assumed that back-reflected signals that are received during reception have insignificant power level because they come from reflections at relatively far positions with respect to the receiver.

In the WDD case, optical filtering can be used to mitigate the problem from backrelection and leakage because these signals are of different wavelength from the intended received signal. This way, the WDD scheme can have lower penalty in power budget. Even so, SDD scheme is relatively the best in this consideration, simply because the leakage is non-existent and the notion of backreflection going to the receiver is irrelevant. Also, compared to other cases, typical devices for SDD in general have the lowest insertion loss. As such, the SDD can provide the best power budget. This then also has a positive effect on network reach.

Components-saving: It can be seen that for FDD, TDD and WDD, half the number of fiber strands are used than in SDD case. The difference is quite large especially for PONs because there are many links between the OLT and ONTs/ONUs. Also in the SDD case, other optical devices such as passive couplers with the associated connectors must be double in number. On the other hand, FDD, TDD and WDD need more specialized components, e.g., optical circulators (FDD & TDD), wavelength-selective couplers and two types (for each wavelength) of light sources and possibly photodetectors (WDD). It’s not easy to find the clear conclusion, but it can be said that overall, all schemes have about the same merit in this consideration.

System capacity: By its own nature, a TDD scheme inevitably incurs a penalty in system capacity. This is caused by the propagation delay and a finite switching time. For other duplexing schemes, this problem is non-existent. For WDD and SDD schemes, even more capacity can be gained compared to FDD case. This can be explained as follows. In FDD case, separate sets of subcarriers for upstream and downstream transmissions are used, whereas in WDD and SDD schemes, more or less the same subcarriers can then be used both for upstream and downstream transmissions; hence, additional capacity is available.

Conclusion

Five considerations have been taken for duplexing methods under study in this paper. It can be summed up that SDD scheme has the best merit compared to other schemes. WDD scheme can be a good alternative if the cost-saving effect of using less fiber strands and related components proves to be significant.

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