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METHOD AND SYSTEM FOR TESTING FOR DEFECTS IN A MULTIPATH OPTICAL NETWORK

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METHOD AND SYSTEM FOR TESTING FOR DEFECTS IN A MULTIPATH OPTICAL NETWORK

FIELD OF THE INVENTION

The present invention relates to the field of optical tests and measurement and more particularly concerns a method, a system and devices providing for the identification and localisation of defects in one of multiple light paths of an optical network.

BACKGROUND OF THE INVENTION

Optical network testing, monitoring and management is an important issue for a multitude of telecommunication applications, such as fiber-to-the-home FTTH, access and metro passive optical networks PONs, and wavelength division multiplexing WDM communication networks.

A. Standard OTDR

The concept of standard optical time domain reflectometry (OTDR), as shown in FIG. 1 (PRIOR ART), consists of detecting the Rayleigh and/or Brillouin backscattered and reflected signals from one transmitted short, high-power optical pulse. The OTDR theoretically measures the impulse response of the waveguide at the wavelength of the transmitted OTDR pulse. This principle is widely used in the installation and monitoring of traditional point-to-point optical fiber networks. During installation, the OTDR testing is achieved for all standard bands to verify the node-to-node (or end-to-end) loss budget. All events that involve a refractive index change in light path, hence contributing to a power loss, gain, reflection ghost or combination of them, could be measured. Every connector, splice, fusion, bending, partial or complete break, fiber termination or derivation contributes to a specific behaviour in the impulse response of the waveguide observed in the OTDR equipment. Interpretation of these events, from the captured impulse response, requires high technical expertise.

As illustrated in FIG. 2 (PRIOR ART), in the case of complex waveguides, the presence of multiple light paths leads to the transmitted pulse being split into multiple sub-pulses, each of which generates individual backscattered and reflected signals, representing individual impulse responses of the different light-paths. The OTDR, however, receives the cumulative (or the sum) of these individual impulse responses, and is incapable of distinguishing individual impulse responses from the cumulative signal. When the number of these light paths increase, even expert human intervention is incapable of sorting out individual responses. In FIG. 2, a hypothetical example of an optical multi-path waveguide is illustrated with PRIOR ART standard OTDR. The OTDR pulse enters the multi-path waveguide (DUT: device under test) from a port P0, is split into multiple sub-pulses (N in FIG. 2), each of which travels through a specific path. N different paths from port P0 to Pi where i=1 to N, are shown with N optical paths h0,1 to h0,N. Every sub-pulse will generate backscattered power in addition to reflected depending on the path traveled. The OTDR receives backscattered and reflected power that is a sum of all scattered and reflected powers from all the N paths traversed by the N sub-pulses.

Let $I_0(t,\lambda)$ be the impulse response of the multi-path waveguide observed from the IN/OUT port P0. This is equal to the sum of all individual impulse responses of the N paths.

$$I_0(t,\lambda) = \sum_{i=1}^{N} I_{0,i}(t,\lambda))$$

where $I_{0,i}(t,\lambda)$ is the impulse response of the path h0,i., where i=1 to N. The received signal at the OTDR is:

$$S(t,\lambda) = \Pi(t,\lambda) * I_0(t,\lambda) = \Pi(t,\lambda) * \sum_{i=1}^{N} I_{0,i}(t,\lambda)$$

where $\Pi(t,\lambda)$ is the transmitted pulse function, and * is the convolution operator in the time domain.

There is a need for a solution for characterizing multi-path optical waveguides, hence allowing the monitoring equipment to automatically characterise and monitor the individual optical paths of multi-path waveguides.

B. FTTH and PON

Passive splitters (PS) and time division multiplexing (TDM) based fiber-to-the-home (FTTH) and other passive optical networks (PONs) are practical examples of complex, large multi-path optical waveguides. Standard monitoring system based on the prior art of FIG. 1 cannot function with FTTH and PONs because of the complex topology (e.g. tree or star) consisting of a large number of parallel light paths. The OTDR receiver observes reflections coming from a large number of parallel paths, that all overlap in time. Unlike WDM networks, where a given wavelength signal travels through a unique linear light path (even through multiplexers, switches etc.), allowing hence the OTDR to easily discriminate subsequent reflections, PON topology results in a multi-path phenomenon generating superposed reflections.

The OTDR trace at the central office (CO) is a linear sum of the backscattered and reflected power from all the network branches. It is difficult, and even impossible, for the CO Manager even with great expertise to distinguish events in one branch from events in other branches.

FTTH-PONs seem to be the ultimate winning solution for tomorrow’s last/first mile bottleneck. Important FTTH deployments have been carried out in North America, Europe and Japan, over the last decade. Starting from 1:1 (1 fiber to 1 customer) in the early 90s, PS together with TDM technologies have enabled up to 1:128 for the GPON standard (ITU G. 984) with forward error correction (FEC). It is recently reported a test bed with 1:256 PS, and future extra large XL-PON systems are aimed at splitting factors of up to 1024.

Many FTTH management problems result from the very little information available to the CO manager about the network. This directly affects the quality of service and dramatically increases the administration, the maintenance and the provisioning costs. For example, when two branches experience equidistant failure events they are indistinguishable. Even when a fiber-fault results in an unambiguous event, the faulty branch is not identified, requiring a truck-roll tour and outside intervention of

technicians. Every branch must be checked separately from its end by means of upstream power meter and/or OTDR transmission in order to identify the faulty one. Moreover, when an optical network unit (ONT) is not communicating with the CO, the manager cannot make a remote diagnosis and determine the cause: whether this is due to a fiber cut or simply because the ONT is disconnected or turned OFF. Few solutions for In-Service TDM/PON management have been proposed [1-3]; all of them are impractical mainly because their capacity is limited to a few tens of customers. FIG. 3 illustrates all the PRIOR ART approaches described in the following.

FIG. 3a) shows one PRIOR ART approach [Tanaka, K., Tateda, M. and Inoue, Y. "Measuring the individual Attenuation Distribution of Passive Branched Optical Networks," IEEE Photonics Technology Letters, Vol. 8, No. 7, July 1996.] that addresses the problematic using a passive splitter assembled with a WDM de-multiplexer and an active optical switch PS-R (i.e., passive splitter-router). This proposal, made in 1996, before the emergence of WDM networks in the 1550 nm band, exploits the 1550 nm band for the monitoring of the different PON branches. The data is carried by the 1310 nm wavelength. With the 1550 nm band partitioned in a WDM way, each waveband is dedicated for the monitoring of one specific branch of the PS. The active switch PS-R, cyclically selects the branch to be monitored, and a tuneable OTDR laser is used to generate the wavelength appropriate for the branch. One optical reflector (not necessarily wavelength selective) is placed at every branch's end in order to alleviate the OTDR dynamic range requirements.

FIG. 3b) shows another PRIOR ART approach [Chan, Chun-Kit, Tong, Frank, Chen, Lian-Kuan, Ho, Keang-Po and Lam Dennis, "Fiber-Fault Identification for Branched Access Networks Using a Wavelength-Sweeping Monitoring Source," IEEE Photonics technology Letters, Vol. 11, No. 5. May 1999.] that makes use of a single Bragg grating with a distinct wavelength at the end of every branch of the network. A tuneable laser is used at the central office to cyclically interrogate these Bragg gratings. One reflection occurs from any healthy branch, and no reflection occurs when the branch is faulty. The CO manager can automatically detect and identify the unhealthy branch. Each PRIOR ART in FIG. 3a) and FIG. 3b) makes use of tuneable lasers, allowing localization of the fault in addition to identifying the unhealthy branch.

FIG. 3c) shows another PRIOR ART approach [Ye, Chien-Hung, Chi, Sien "Optical fiber-fault surveillance for passive optical networks in S-band operation window" OPTICS EXPRESS, Vol. 13, No. 14, 11 July 2005.]. The monitoring principle in this approach consists of a tuneable very long ring laser, made by an EDFA as an amplification medium, placed in the central office, and Bragg gratings at the end of the branches that close the ring. The laser is tuned using a tuneable passband filter. When a branch is healthy, the ring is closed and the lasing process works well, indicating the good state of the branch. When a fiber-fault occurs, the grating, is disconnected from the fiber branch, the ring is open, and the lasing will not be possible, indicating the unhealthy state of that branch. This is unfortunately a very complex system that consumes large bandwidth that would be more profitably deployed for data transmission.

FIG. 4a) shows another PRIOR ART approach [Park, S.-B., Jung, D.K., Shin, H.S., Shin, D.J., Hwang, S., Oh, Y. and Shim, C., "Optical fault monitoring method using broadband light source in WDM-PON," Electronic Letters, Vol. 42, No. 4, 16th February 2006] proposed for a WDM-PON system where every user is dedicated one wavelength for data and another for monitoring. The system assigns the C band for data and the L band for monitoring. FIGs. 4a), b) and c) describe three different settings of reflectors to be placed at the branches' ends. The first uses a fiber loop with a circulator, the second uses a wavelength splitter with standard reflector and the third uses an in-line Bragg grating before the fiber termination. A major drawback of this system is the use of 50 % of the wavelength resources for monitoring. In addition, the capacity (in terms of number of branches) saturates with 16 to 32 customers.

The PRIOR ART systems illustrated in FIG. 1, FIG. 3 and FIG 4, are impractical for high numbers of subscribers due to the very large spectrum to be sliced, i.e., one slice for every network leg. For 32 home customers (respectively 128 in GPON with FEC), and using narrow slice width of 0.8 nm, a total bandwidth of 25.6 nm (respectively 102.4 nm) is required [2,4].

This lack of an in-service live monitoring solution becomes more critical with the coming advanced and prospective PON architectures like wavelength division multiplexing WDM/PON or hybrid TDM/WDM-PON (where a TDM-PON like system is built over every wavelength in a passive WDM network). These architectures promise many hundreds of FTTH customers per fiber. This calls for an extremely high capacity PON monitoring technology.

SUMMARY OF THE INVENTION

In accordance with one aspect of the present invention, there is provided a method for testing an optical network for defects between a network node and a plurality of network locations, each network location being connected to the network node through a corresponding light path, said method includes the steps of:

a) transmitting a pulsed monitoring light signal from the network node to each of the network locations through the corresponding light path;
b) providing an encoder in each of the light paths proximate the corresponding network location, each encoder reflecting the monitoring signal back towards the network node and encoding the reflected monitoring light signal according to an encoding function, the encoding function of each encoder having a low cross-correlation to the encoding function of all other encoders;
c) receiving a return signal at the network node corresponding to the reflection of the monitoring light signal in said light paths; and
d) for at least one of said light paths:
    i) decoding the return signal according to a decoding function correlated to the encoding function associated with said light path, thereby obtaining a decoded return signal; and
    ii) analysing the decoded return signal to

determine therefrom if any defect is present in said light path.

In accordance with another aspect of the present invention, there is also provided a system for testing an optical network for defects between a network node and a plurality of network locations, each network location being connected to the network node through a corresponding light path, said system comprising:

- transmitting means for transmitting a pulsed monitoring light signal from the network node to each of the network locations through the corresponding light path;
- an encoder associated with each of the light paths and provided therein proximate the corresponding network location, each encoder reflecting the monitoring signal back towards the network node and encoding the reflected monitoring light signal according to an encoding function, the encoding function of each encoder having a low cross-correlation to the encoding function of all other encoders;
- receiving means for receiving a return signal at the network node corresponding to the reflection of the monitoring light signal in said light paths;
- decoding means for decoding the return signal according to any one of a plurality of decoding functions, thereby obtaining a decoded return signal, each decoding function being correlated to the encoding function associated with one of the light paths; and
- analysing means for analysing the decoded return signal to determine therefrom if any defect is present in the light path associated with the corresponding decoding function.

In accordance with yet another aspect of the invention, there is further provided a set of devices for installation in an optical network for testing the same for defects between a network node and a plurality of network locations, each network location being connected to the network node through a corresponding light path, said set of devices comprising:

- a light generating module for generating a pulsed monitoring light signal, said light generating module having a light output connectable to said optical network for transmitting the monitoring light signal from the network node to each of the network locations through the corresponding light path;
- a plurality of encoders each connectable to one of the light paths proximate the corresponding network location for reflecting the monitoring signal back towards the network node, each encoder having an encoding function for encoding the reflected monitoring light signal, the encoding function of each encoder having a low cross-correlation to the encoding function of all other encoders;
- a processing module having a light input for receiving a return signal at the network node corresponding to the reflection of the monitoring light signal in said light paths, said processing module having decoding means for decoding the return signal according to any one of a plurality of decoding functions, thereby obtaining a decoded return signal, each decoding function being correlated to the encoding function associated with one of the light paths, and analysing means for analysing the decoded return signal to determine therefrom if any defect is present in the light path associated with the corresponding decoding function.

Other features and advantages of the present invention will be better understood upon reading of preferred embodiments thereof with reference to the appended drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 (PRIOR ART) is a diagram illustrating standard optical time domain reflectometer OTDR based on light backscattering and reflection principle, conceived for characterisation of single light-path waveguides only and point-to-point optical fiber links.

FIG. 2 (PRIOR ART) is a diagram illustrating the problematic faced by standard OTDRs when applied to characterizing multi-path optical waveguides such us optical passive splitters in standard FTTH, and general architectures of passive optical networks. An optical network is presented here like a complex and large multi-path optical waveguide.

FIGs. 3A to 3C (PRIOR ART) show different prior art approaches for addressing the problematic illustrated in FIG. 2; FIG. 3A shows one prior art approach, proposed in 1996, that addresses the problematic using passive splitter concatenated with an active optical switch PS R; FIG. 3B shows another prior art approach, proposed in 1999, that makes use of Bragg gratings placed in the ends of the branches to help identify the unhealthy branches; and FIG. 3C shows another prior art approach to the problematic similar to the of b) but suggesting the use of the under employed S-band.

FIG. 4A (PRIOR ART) shows another prior art approach for a WDM based PON, where every client is dedicated two wavelengths, one for data and the other for monitoring; FIGs. 4B and 4C show two different possible reflecting schemes provided at the clients of such a network.

FIG. 5 is a diagram illustrating the general principle of a method and system according to a preferred embodiment of the present invention.

FIG. 6 is a block diagram of a system for testing an optical network for defects according to an embodiment of the invention, where the decoding functions are implemented using optical components.

FIG. 7 is a state diagram showing the step of a method for testing an optical network for defects according to an embodiment of the invention, which may be implemented using the system of FIG. 6.

FIG. 8 is a block diagram of a system for testing an optical network for defects according to another embodiment, where the decoding functions are also implemented using optical components.

FIG. 9 is a state diagram showing the step of a method for testing an optical network for defects which may be implemented using the system of FIG. 8.

FIG. 10 is a block diagram of a system for testing an optical network for defects according to an embodiment of the invention, where the decoding functions are) is performed on the electrical field using waveform

functions selected to perform the function similar to that in optics.

FIG. 11 is a state diagram showing the step of a method for testing an optical network for defects according to an embodiment of the invention, which may be implemented using the system of FIG. 10.

FIG. 12 is a block diagram of a system for testing an optical network for defects according to an embodiment of the invention, where the decoding functions are) is performed in electronics using modified decoding technique.

FIG. 13 is a state diagram showing the step of a method for testing an optical network for defects according to an embodiment of the invention, which may be implemented using the system of FIG. 12.

FIG. 14 is a block diagram of system similar to that of FIG. 12 but illustrating the importance of pseudo-noise coding prior to the pulse transmission in order to increase the signal to noise ratio at the receiver.

FIG. 15 is a state diagram showing the important processing and decision steps according to the embodiment of FIG. 14.

FIG. 16 is a schematic representation of a system according to an embodiment of the invention implemented in a TDM/TDMA FTTH optical network.

FIG. 17 is a schematic representation of a system according to an embodiment of the invention implemented in a WDM optical network.

FIG. 18 is a schematic representation of a system according to an embodiment of the invention implemented in a hybrid TDM/TDMA over WDM passive optical network.

FIGs. 19 and 20 are schematic representations of systems according to an embodiment of the invention implemented in multipath optical waveguide composed of WDM passive ring networks.

FIGs. 21A to 21I show alternative embodiments of encoders for use in a system according to the present invention, all for time-dependent encoding functions.

FIG 22 shows design charts for time-only dependent waveforms inspired from optical orthogonal code families.

FIG. 23 shows one embodiment of a coding function with time and wavelength dependent coding waveforms.

FIG. 24 shows one embodiment of a coding function with wavelength-only dependent coding waveforms.

DESCRIPTION OF PREFERRED EMBODIMENTS OF THE INVENTION

Generally, the present invention relates to a method and system for testing an optical network for defects between a network node and a plurality of network locations.

Throughout the present application, the expression "optical network" is understood to refer to any collection of light paths connecting together different points or locations. The terms "optical" and "light" are used herein to refer to any appropriate portion of the electromagnetic spectrum, and are not limited to the visible spectrum only. The method and system disclosed herein may be particularly advantageous for characterizing multi-path optical waveguides and managing FTTH, PONs, and WDM optical networks or the like. Although the description below refers mainly to such embodiments, one skilled in the art will understand that the present invention may easily be adapted to different applications without departing from the scope of protection. In an alternative example, the optical network may be embodied by a multipath waveguide. By "defects", it is understood a break in a light path, or any other event, damage, alteration, wear, etc which may interrupt or affect light transmission therein.

Referring to FIG. 5, there is schematically illustrated an optical network 30 provided with a system 32 according to a preferred embodiment of the invention. Each network location is here schematized as a port (P1, P2, … PN) connected to the network node P0 through a corresponding light path (h0,1, h0,2, … h0,N). In a FTTH network, each network location may be embodied by a customer site, and the network node by the Central Office. The method and system of the invention in this context would allow the monitoring of the entire network. The invention may alternatively be applied between any plurality of network locations linked to a single network node, as will be easily understood by one skilled in the art.

The method of the present invention first includes transmitting a pulsed monitoring light signal 34 from the network node P0 to each of the network locations (P1, P2, … PN) through the corresponding light path (h0,1, h0,2, … h0,N). The transmitted pulse function is represented as $\Pi(t,\lambda)$.

An encoder OCM is provided in each of the light paths, at or proximate the corresponding network location. In practice, the encoder OCM may for example be positioned at the premises of each customer. It will be understood that the encoders need not be at the extremity of any given light path, but that the placement of an encoder will determine the portion of the corresponding light path being monitored as part of the method and system of the invention. Each encoder OCM reflects the monitoring signal 34 back towards the network node P0, and encodes the reflected monitoring light signal according to an encoding function $e_i(t,\lambda)$. The encoding function of each encoder has a low cross-correlation to the encoding function of all other encoders, as will be explained in more detail further below. The encoding functions may for example be designed to be orthogonal or pseudo-orthogonal. Depending on the application context, the coding waveforms embodying the encoding functions could be time-only, wavelength-only, or time and wavelength dependent functions, as well as phase dependent, polarisation dependent or any combination of these parameters. The encoders themselves may be embodied by reflective components such as multi-structure Bragg gratings, or any other coding technology. Examples of encoders for time modulation of the monitoring signal are shown at FIGs. 21A through 21I and are explained further below.

The method next involves receiving a return signal 36 at the network node, corresponding to the reflection of the monitoring light signal 34 in said light paths. The return signal will include the encoded monitoring signal from every light unbroken light path, as well as any reflections occurring within the network. The return signal may be expressed as follows:

$$S(t,\lambda)=\Pi(t,\lambda)*\sum_{i=1}^{N} I_{0,i}(t,\lambda)*e_i(t,\lambda),$$

where $I_{0,i}(t,\lambda)$ is the impulse response of the path h0,i.

It will be noted that the equation above assumes that the encoding functions depend on both time and wavelength, but that dependency on a single parameter or on different ones may be considered as explained above.

Information on defects in any given one of the light paths (h0,1, h0,2, … h0,N) may be obtained by decoding the return signal 36 according to a decoding function correlated to the encoding function associated with this light path. The decoded return signal thereby obtained is analysed to determine therefrom if any defect is present in the light path, and possibly, where along this path. The decoding of the return light beam may be performed optically, or electronically. Different manners of performing such a decoding and analysis are explained below in connections with the embodiments of FIG. 6, FIG. 8, FIG. 10, FIG.12 and FIG. 14.

A. Embodiments of the system and method of the invention

FIG. 6 is a block diagram illustrating a first preferred embodiment of a system 32 in which the decoding functions are designed using optical components and performed on the optical field of the return signal before any detection. In the illustrated embodiment, the system 32 is shown as having a light generating module 46 including a laser 42, or other light source, generating the pulsed monitoring signal 34. The laser may be embodied by any appropriate device known in the art, and is driven by a laser control 44 as also well known in the art. a first circulator 48 directs the monitoring light signal 34 from the laser 42 to the optical network, where it is distributed along multiple light paths and reflected by an encoder at the end of each, and directs the return signal 36 received from the network to a processing module 50 including both decoding and analysing means.

Preferably, a bank of optical decoders 38, each the mirror image of one of the encoders of the system, is provided. An optical switch 40 preferably directs the return signal 36 to each decoder 38, either as needed or successively. A processor 52 is preferably provided and incorporates a detector 56 for transforming the decoded signal into an electronic decoded signal, and appropriate applications to analyse this electronic decoded signal. A second circulator 54 connects the first circulator 48, optical switch 40 and processor 52.

For illustration purposes, the decoding operation may be mathematically modeled by time convolution of the return signal $S(t,\lambda)$ with the decoder functions of each light path $d_i(t,\lambda)$, i=1 to N. The decoded signal is therefore expressed as:

$$\begin{aligned}R_i(t,\lambda)&=S(t,\lambda)*d_i(t,\lambda)\\&=\Pi(t,\lambda)*\sum_{j=1}^{N} I_{0,j}(t,\lambda)*e_j(t,\lambda)*d_i(t,\lambda)\end{aligned}$$

Hence

$$\begin{aligned}R_i(t,\lambda)&=\Pi(t,\lambda)*I_{0,i}(t,\lambda)*e_i(t,\lambda)*d_i(t,\lambda)\\&\quad+\Pi(t,\lambda)*\sum_{j=1,j\neq i}^{N} I_{0,j}(t,\lambda)*e_j(t,\lambda)*d_i(t,\lambda)\\&=\Pi(t,\lambda)*I_{0,i}(t,\lambda)*AUT_i(t,\lambda)\\&\quad+\Pi(t,\lambda)*\sum_{j=1,j\neq i}^{N} I_{0,j}(t,\lambda)*CROSS_{i,j}(t,\lambda)\end{aligned}$$

where:

$$AUTO_i(t,\lambda)=e_i(t,\lambda)*d_i(t,\lambda)$$
$$\textit{and}\quad CROSS_{i,j}(t,\lambda)=e_j(t,\lambda)*d_i(t,\lambda)$$

represent the so-called autocorrelation and cross-correlation functions of the codes.

FIG. 7 is a state diagram explaining the workings of the decoding and analysing of the return signal using the system of FIG. 6. This method includes sending 100 the return signal to the processing module, and selecting 102 one of the light path h0,i for decoding. The selected light path is correlated 104 using the decoding function associated with the same light path. In FIG. 6, this is accomplished by setting the switch 40 to close the circuit to the appropriate optical decoder 38. A decoded signal for this particular light path is thereby obtained. The method then preferably includes a step of identifying 106 an autocorrelation major peak in this decoded signal, corresponding to the position of the encoder along the light path. This is preferably done electronically by the processor. If such an autocorrelation major peak is not identified, then the return signal does not includes a component encoded by the corresponding encoder, indicating that the light path is broken; a message to this effect can be generated 110. If the autocorrelation major peak is identified 112, then the processor searches 114 the decoded return signal for at least one reflection peak. If one or more such peaks are detected 116, they are each interpreted 118 as a potential defect along said light path (splice, bending, faulty connection, etc). The profile of the light path may be traced 120 as the time delay corresponding to each minor peak can be correlated to a position along the light path.

FIG. 8 is a block diagram illustrating a system according to a second preferred embodiment. The de-correlating (decoding) is also performed on the return signal's optical field before the TE detector. In addition to all blocks of FIG. 6, FIG. 8 includes a re-encoding block 58, OCMi, i=1 to N, with an optical switching block 60having two possible optical paths. The first path (a-b-e-f) connects the decoder directly to the photodetector, avoiding the re-coding block; this makes the scheme identical to that of FIG. 6. The second path, (a-c-g-f) feeds the decoded signal to the re-encoding block tuned to the respective encoder, and then sends the re-encoded signal to the photodetector. The switch is tuned to this second path when a fault is detected in a specific light path. The re-encoding simply regenerates the return signal prior to the decoder.

The embodiment of FIG. 8 focuses on the case where one (e.g, branch k) among the N light paths is interrupted. The interruption reflects back a pulse with a reflectivity β. The return signal at the monitoring equipment called OC-

OTDR is as follows:

$$S(t,\lambda)=\beta\Pi(t,\lambda)*J_{0,k}(t,\lambda)$$
$$+\Pi(t,\lambda)*\sum_{i=1,i\neq k}^{N}I_{0,i}(t,\lambda)*e_i(t,\lambda)$$

where $J_{0,k}(t,\lambda)$ is the impulse response of the interrupted light path from the central office to the fault location. The decoder tuned to the kth light path has output signal:

$$R_k(t,\lambda)=S(t,\lambda)*d_k(t,\lambda)$$
$$=\beta\Pi(t,\lambda)*J_{0,k}(t,\lambda)*d_k(t,\lambda)$$
$$+\Pi(t,\lambda)*\sum_{i=1,i\neq k}^{N}I_{0,i}(t,\lambda)*e_i(t,\lambda)*d_k(t,\lambda)$$
$$=\beta\Pi(t,\lambda)*J_{0,k}(t,\lambda)*d_k(t,\lambda)$$
$$+\Pi(t,\lambda)*\sum_{j=1,i\neq k}^{N}I_{0,i}(t,\lambda)*e_i(t,\lambda)*d_k(t,\lambda)$$
$$=\beta\Pi(t,\lambda)*J_{0,k}(t,\lambda)*d_k(t,\lambda)$$
$$+\Pi(t,\lambda)*\sum_{i=1,i\neq k}^{N}I_{0,i}(t,\lambda)*CROSS_{i,k}(t,\lambda)$$

The first term of the decoded signal is a correlation of the kth decoder function and the impulse response of the remaining part of the kth light path; no autocorrelation function exists in this term. The second term is a sum of cross-correlations of the kth decoder with all the healthy paths' encoders convolved with their respective paths' impulse responses. The OC-OTDR TE, due to the prior measurements and identifications, already knows the second term. The OC-OTDR TE could use this prior information to derive the first term. Otherwise, the OC-OTDR TE can achieve a re-encoding of that decoded signal using the re-encoding block described in FIG. 8, tuned to the kth encoder.

Let's $RR_k(t,\lambda)$ be the output signal of the re-encoding block:

$$RR_k(t,\lambda)=S(t,\lambda)*d_k(t,\lambda)*e_k(t,\lambda)$$
$$=\beta\Pi(t,\lambda)*J_{0,k}(t,\lambda)*AUT_k(t,\lambda)$$
$$+\Pi(t,\lambda)*\sum_{j=1,i\neq k}^{N}I_{0,i}(t,\lambda)*CROSS_{i,k}(t,\lambda)*e_k(t,\lambda)$$

The re-encoded signal is composed of two terms; the first is a correlation of the autocorrelation function with the impulse response of the remaining part of the interrupted kth path. The second terms are re-coded (or re-spread) cross-correlation functions, which represents the interference. The OC-OTDR TE extracts the impulse response $J_{0,k}(t,\lambda)$. The position (or the delay) of the autocorrelation function $AUT_k(t,\lambda)$ indicates the fault position in the kth path. This embodiment is capable of not only identifying the faulty light-path (or fiber) but also determining its distance from the central office. FIG. 9 is a state diagram showing the key process steps of the multi-path waveguide characterisation or optical network characterisation and monitoring, according to the embodiment of FIG. 8.

Note that the previous discussion considers the case when only one light path is interrupted at a time. If more than one branch fails in the same observation time, the analysis will be more complex. Two cases could be considered: (1) the failed paths simultaneously fail in different distances to the CO, this is very unlikely; or (2) the failed paths fail in the same distance to the CO, this is the most likely (frequently due to cable failure or cut). In case (1), which is the most unlikely case, two or more autocorrelation peaks will appear after the re-encoding step. Identifying which peak corresponds to which path is very difficult or impossible. In case (2), however, only one autocorrelation peak appears for all the unhealthy paths since all of them failed in the same location. This case is easy to detect and the embodiment of FIG. 8 applies well for this case.

FIG. 10 is a block diagram of a system 32 according to the another preferred embodiment: the de-correlating (decoding) is performed on the electrical field using waveform functions selected to perform the function similar to that in optics. For this purpose, electronic decoders 39 are provided after the detector 52. Optionally, electronic re-encoders 59 may be provided and perform electronically the same function as the re-encoding block of FIG. 8.

Performance of OCDM decoding in electronics after the detection is extremely rare in data communications. For data communications we typically try to transfer to optics as many electronic functions as possible. In the case of this application, it is not necessary to achieve very high transmission bandwidth. Also, electronics of 1 or 2 GHz speed is no longer expensive. The decoding function could be performed at that speed using low cost electronic devices. This leads to significant cost savings by eliminating optical components to separately decode each client. Moreover, electronic processing of the decoding and the re-encoding of FIG. 6 and FIG. 8 reduces the power loss budget of the system by 10 dB or more since it removes all the decoding loss. Furthermore, this enables developing and applying complex detection algorithms and performing the decoding of all the branches impulse responses simultaneously instead of cyclically. The state diagram of FIG. 11 shows the important processing and decision steps according to the embodiment of FIG. 10.

FIG. 12 is a block diagram of a system according to the yet another embodiment: the de-correlating (decoding) is performed in electronics using modified decoding technique. The decoder weights or otherwise takes into account, the whole or a part of the available information, including all the encoders' properties and the calculated transfer functions of the other paths. The system of FIG. 12 is preferably provided with a processor 52 incorporating a decoding application for parallely decoding the electronic return signal according to each of the decoding functions, thereby electronically obtaining the decoded return signal for each of the light paths, and a correlation application searching each of the decoded return signal for an autocorrelation major peak corresponding to a position of the encoder along the corresponding light path, and identifying this corresponding light path as broken if the autocorrelation major peak is not located.

FIG. 13 is a state diagram showing the important processing and decision steps according to the embodiment of FIG. 12. This method includes detecting and sending 121 the return signal to the processing

module, and electronically correlating 122 the detected signal with all the decoding waveforms. A plurality of decoded signals, one for each light path is thereby obtained. The method then preferably includes a step of analysing 124 all the decoded signals to identify an autocorrelation major peak, corresponding to the position of the encoder along the light path. This is done electronically by the processor.

If such an autocorrelation major peak is not identified 126, then the return signal does not includes a component encoded by the corresponding encoder, indicating that the light path is broken. The method then preferably includes analysing 128 the decoded signal for this light path using the information from all the other paths, information from prior measurements (i.e. the results of the same analysis performed at a previous time), or both. This may allow the identification 130 of a reflection peak corresponding to the break location along the light path, and consequently an estimation 132 of the location of the break along the path. A message 134 is then displayed, to the effect that a break has been located and where along the path. In the event that reflection peak corresponding to the break location is not identified, a message to this effect can also be displayed 136.

As with the embodiment of FIG. 7, if the autocorrelation major peak is identified 112, then the processor searches 114 the decoded return signal for at least one reflection peak. If one or more such peaks are detected 116, they are each interpreted 118 as a potential defect along said light path. it will be noted that not all reflection peaks are the result of a defect, as a splice, a connector, etc may also generate such a peak. The correlation application however knows the location of fixed network reflection sources, and can differentiate them from reflection peaks associated to the potential defects. The profile of the light path may be traced 120 as the time delay corresponding to each minor peak can be correlated to a position along the light path.

FIG. 14 is a block diagram of a system according to another embodiment similar to that of FIG. 12 but illustrating the importance of pseudo-noise modulation or coding of the monitoring signal prior to transmission through the network, in order to increase the signal to noise ratio at the receiver. FIG. 15 is a state diagram showing the important processing and decision steps according to the embodiment of FIG. 14. Pseudo-noise noise modulation is well known in the art, and reference can for example be made to [].

It should be noted that in the embodiments of FIGs. 10, 12 and 14, electronic detection is applied for OCM codes that are coded only in the time domain, as wavelength information will be lost. When the OCM codes are two dimensional, we have to apply optical de-correlation only, or detect every wavelength separately, before making the electronic analysis.

Electronic based processing embodiments illustrated in FIG. 10, FIG. 12 and FIG. 14 are clearly less cumbersome and expensive than that of FIG. 6 and FIG. 8. The monitoring equipment should cost not more than 10% more than traditional OTDR equipment. We expect the cost of the monitoring equipment to be 1500 to 2500 $ depending on the processing functions to be included. The cost of the encoders to be placed at the fiber ends should range from 10 to 100 $ each, depending on the volume and the selected components as shown in FIG. 23.

It will be noted that the present invention also relates to a set of devices for installation in an optical network for testing the same for defects. The set of devices includes a light generating device, a plurality of encoders and a processing module which integrates the decoding and analysing components of any of the system embodiments described above. These devices may be provided as a kit to service providers for installation in an already existing network or in a new one.

B. Examples of applications with time-dimension encoding

For the purpose of simplicity, examples are given below with applications that make use of one dimensional, time domain codes; i.e., all codes share one monitoring wavelength. In the following the practical implementation of the invention is addressed in real examples of networks including, standard FTTH, PONs, and WDM networks. It will however be understood by one skilled in the art that although the present description focuses on the implementation of time domain codes, the present invention is not limited thereto and could includes any other possible coding techniques in the context of the method and strategy of the present invention to characterize multi-path waveguides or monitor optical networks. The proposed technique is referred to herein as Optical-Coding based Optical-Time-Domain-Reflectometry (OC-OTDR) since this fulfills the traditional OTDR like-role, but in the context of complex multi-path waveguides. Traditional OTDR suffers from cumulated multi-path backscattered and reflected signals, making it impossible to discriminate the impairments of one specific optical path from others.

FTTH and PON applications

Here embodiments as shown above are applied for specific cases of multi path waveguides like FTTH, PON, or more complex ring WDM networks. The present OC-OTDR technique could be straightforwardly applied to the characterization, installation, monitoring and management of FTTH, PON, and more complex ring WDM networks. Using time domain codes, this requires only one wavelength, preferably in the 1650 nm wavelength already reserved for standard FTTH TDM-PON monitoring, or the non-standard but inexpensive 1625 nm wavelength. The present technique is also scalable for more advanced and complex PON networks, always using a single wavelength. As illustrated in FIG. 17, in this embodiment every network branch is terminated by a standard passive wavelength selector (WS), widely used in PONs, isolating the standard monitoring U band from the other data bands at the front of every ONT and at the CO as well. If two dimensional or wavelength-only dimensional codes are used, a wider wavelength band is required for monitoring; the standard U band could be also effective for these kinds of codes.

The transmission section of the OC-OTDR TE at the CO (FIG. 16) preferably consists of a U band pulsed laser driven by a processor to transmit short pulses with a predetermined low frequency rate (a few megahertz or lower) and adequate power to support the back and forth cumulative loss. Any of the embodiments of FIG. 6 to 15

could be considered. Every pulse propagates through the tree network, is split at the PS, is coded by encoders OCMi, i=1 to N, and is then reflected back to the CO. In single wavelength embodiments, the encoder may consist of a passive device that fragments an incoming pulse into a number of p sub-pulses distributed in time according to a specific code, i.e., direct sequence coding in the time domain. Every encoder at the branch termination implements a unique code.

Preferably, the proposed network management system is a modified form of direct sequence DS-OCDM, and the codes used are also the so-called optical orthogonal codes (OOC). The PS (coupler) combines the upstream encoded pulses together as in standard OCDM. In the CO, a tunable DS-decoder, such as, for example, the optical switch 40 and a bank of fixed decoders 38 of FIG. 6 (similar to encoders but introducing delays in reverse order), discriminates responses coming from different branches of the tree network. Every healthy branch in the network contributes an autocorrelation peak. A missing autocorrelation peak indicates the corresponding network branch is broken or exhibits abnormal power loss. Furthermore, the height of the detected autocorrelation peak in the normally working branches, indicates the cumulative end-to-end loss of the fiber link, including that attributed to the fiber, connectors, splitters, splices, fiber bending, etc. Recall that the present technique provides the network manager the currently missing information about the loss specifically incurred by the fiber link. As explained above, cyclic communication alone between the OLT and ONTs is not sufficient to provide the network manager with information specific to the fiber link.

The systems and methods according to preferred embodiments of the present invention address many of the management challenges described above. Benefits are described qualitatively in this section and the quantitative capacity advantage is studied separately in a following section.

Overcomes OTDR shortcomings: The receiver of the monitoring equipment also acquires a cumulative reflections (or impulse responses) coming from all branches, in addition to that of the feeder. However, all these impulse responses are discernable by means of the decoder and detection process, i.e., the use of orthogonal codes results in the individual impulse responses being overlaid orthogonally. Furthermore, the correlation process is made using the reflected powers and not the Rayleigh backscattered powers. Hence, the dynamic range requirement is very much alleviated, as the backscattered power is about 40 dB lower than that reflected. In the following section we will see how the reflectivity of an encoder could influence its choice and design.

Helps Service Provisioning: New customers are no longer required to be connected with different fiber lengths from those previously installed. This alleviates installation complexity for technicians. Network expansion can continue naturally and is better adapted to unpredictable customer demand. Even for the unused ports in the RN, the placement of encoders is recommended, as this avoids simultaneous reflections to contribute to an undesirable high peak event, which could mask other faults close to the port connectors.

Reduces maintenance complexity and cost: The present system allows the CO Manager to have real-time, full information about all network elements. It does not rely on customer help or calls to diagnosis the network state. The manager will no longer be confused between fiber and ONT faults. Recall that when a fiber fault occurs the carrier is responsible; the proposed technique allows troubleshooting without involving the customer. An ONT fault depends in most cases on the customer himself and is not considered a service interruption. Without complete and in-service live PON monitoring, an outside intervention by technicians is necessary in either case: fiber and ONT faults.

Passive demarcation solution: The encoders of the present invention are preferably passive components that can be placed outside the customer premises (i.e., home); the ONT however could be located inside the customer home, i.e., it is under his control, (sometimes his property), and is his total responsibility. The encoder delimits the service provider control (or ownership) and responsibility from that of the customer.

WDM-PON Application

Fig. 17 shows a WDM-PON network architecture based on WDM multiplexer (upstream) and demultiplexer (downstream). In a WDM-PON, every customer is served by a dedicated wavelength; this allows fixed high bandwidth delivery to all users. Previously proposed PON management uses half of the available wavelengths for data and the other half for monitoring, i.e., every customer is assigned two wavelengths, one for data and another for monitoring. In FIG. 17, there is also shown an architectural solution that allows the technique of the present invention to manage this WDM-PONs with much fewer wavelength resources. In the system, a WS is placed before the 1:K WDM demultiplexer input in order to isolate the monitoring U band from the data bands. A 1:K PS splits the monitoring signal into K copies that are coupled again with data fibers at the demultiplexer K outputs. Upstream and downstream data is assumed here to share the same fiber; other variants could be similarly derived. Of course, any other bi-directional bypass assembly coupling the monitoring signal between the

Tab. 1. Characteristics of the Encoding designs

	Standard Fig. 3(a)	Modified Fig. 3(b)	2^{q+1} splitter Fig. 3(c)	2^q splitter Fig. 3(d)	MBG Fig. 3(e)
Components	2 PSs of 1:2^q	2 PSs of 1:2^q, 1 circulator	1 PS of 1:2^{q+1}	1 PS of 1:2^q	2^qgratings
Pulse loss (dB)	3+6q	3+6q	6+6q	6q+α	-
Number of pulses	2^q	2^q	2^{q+1}	2^q	2^q
Coding loss (dB)	3+3q	3+3q	3+3q	3q+α	7 to 10

input and output branches on either sides of each WDM demultiplexer in the network could equally be used, as one skilled in the art will readily understand. The present technique eliminates all the monitoring wavelengths and makes them available for data, hence doubling the network capacity. Only a single monitoring wavelength is split and distributed to all clients.

TDM/WDM-PON Application

FIG. 18 shows typical TDM/WDM-PON network architecture where a separate TDM system is built over every WDM wavelength. This takes advantages from TDMA and WDM technology in order to dramatically increase the number of users served although per client bandwidth is reduced. Similar to the WDM/PON case, a bi-directional bypass assembly, such as (1+K) wavelength selectors and a 1:K passive splitter to create an alternate path for the OCDM monitoring signal. It should be noted that this method does not control 100% of the fiber paths since the monitoring signal avoids going through the de multiplexers. The architecture, however, controls most of the sensitive segments of these PONs.

WDM RING with all optical Node

FIG. 19 shows another implementation possibility of the present OC-OTDR technology in the case of a multipath optical waveguide composed of a WDM passive ring network. An all-optical node architecture is shown with egress distribution fibers and ports.

WDM RING with hybrid optical/electronic Node

FIG 20 shows another implementation possibility of the present OC-OTDR technology in the case of a multipath optical waveguide composed of a WDM passive ring network. A hybrid electronic/optic node architecture is shown with egress distribution fibers and ports.

Embodiment of encoder designs

FIG 21 shows eight alternatives of implementation embodiments of the coding function, all for time-dependent coding waveforms. Eight designs are proposed for the modified OCM, all appropriate for the disclosed application, in FIG. 21B to 21I. All exploit splitters and delay lines to fragment the incident pulse into sub-pulses, disperse them, gather them back to the fiber and return them to the CO. Each of these encoder designs has its own advantages and drawbacks. The first, FIG. 21B, is the straightforward modification of the standard one of FIG. 21A, and entails 2 ×1:2q splitters and one circulator. The coming pulse enters to the first splitter, exhibits first splitting into 2q sub-pulses, each of which travels a separate fiber delay line with different length. The number of delay lines is equal to the number of ones in the optical code; their lengths correspond to the relative delays between the ones of the code. Since every branch termination is connected to an encoder with a specific code, the delay line lengths change from one encoder to another corresponding to the positions of ones. The second implementation in FIG. 21C requires one 1:2q+1 splitter and eliminates the circulator. The delay lines should be selected in the same way as in FIG. 21B. A number of 2q delay lines are used in this embodiment, each delay line is connected to a separate pair of ports of the splitter. The implementation in FIG. 21D requires only one 1:2q splitter. In this implementation, the ends of the splitter branches are used as Fresnel reflectors. The length of the branches is adjusted corresponding to the half of the delays between the ones in the code. FIG. 21E is an implementation using a multiple Bragg grating (MBG), i.e., a series of discrete gratings at the same wavelength, but with different reflection intensities and physical locations. The number of gratings in the series is equal to the number of ones in the optical code. Also, the relative physical position between the gratings corresponds to the time delay between ones in the optical code.

Advantageously, the encoders may include a resonant cavity dividing the monitoring signal into the sub-pulses, a path length within this resonant cavity being different for each of the encoders. The designs of Fig. 21F and 21G are based on this principle. From an input pulse, they generate a series of periodic pulses with a period equal to twice the length of the cavity. In FIG. 21F the cavity is made by two gratings separated by a delay line with a length equal to T1/2. The reflectivity of both gratings could be easily calculated in order to have the highest power and the most power-equalized pulses in the series. In this design, we consider only the first few pulses as a part of the code and neglect the remaining low power pulses. When we change the length of the fiber T1/2 between the gratings, we obtain a different code. Hence, we differentiate between different codes only using the length of the fiber between the gratings or the cavity length. A family of codes could be appropriate for this design, is called Prime-Periodic codes. It consists in a family of zero/one sequences where the ones are periodically positioned inside long series of zeros with a period equal to prime number (3,5,7,11…) . For weight (number of Ones) equal to 4, these prime codes could be written as: (code1 corresponding to prime number 3: 1001001001, code2 corresponding to prime number 5: 1000010000100001, code 3 corresponding to prime number 7: 1000000100000010000001, and so on).

FIG. 21H is a way to make a cavity using passive splitter and delay line. The designer optimize the selection of splitting ratio in the splitter in order to generate the periodic signal with the highest power and more equalized pulses, at least the beginning of the pulses train. Similarly to Fig. 21H, the length of the delay line fixes the spacing between the ones in the sequence hence differentiating between different codes.

Each of the designs of FIG. 21H and 21I combine two cavities with respective lengths T1and T2. When we combine two cavities with different lengths we have more degrees of freedom in determining codes.

Designing a system according to the present invention preferably takes into consideration the three following parameters: 1) high coding capacity (the number of different codes should be a minimum of 128 for standard GPON with FEC); 2) the modified DS-encoders to be located at network terminations should be low cost and low component count; and 3) the power loss between the incident pulse and reflected coded signal fed back to the fiber should be minimized in order to reduce the required dynamic range of the monitoring system.

The encoder in FIG. 21B is the most expensive because of the circulator (with 1.5 dB loss per pass) and exhibits the highest power loss. The encoder in FIG. 21D is less

expensive, however exhibits very high loss due to the reflection coefficient α, typically about 4% (13 dB). Increasing α to 50%, using special mirrors at the end of the fiber, will make this setting attractive. The encoder in FIG. 21C is less expensive than that in FIG. 21E because of the Bragg gratings compared to PSs, however MBGs has less insertion loss. In Tab. 1 we outline the component count and derive the power loss equations of each of the proposed DS-OCDM encoders. The coding loss illustrated is Tab. 1, is defined as the ratio between the individual powers of a returned and an incident pulse; however, the coding loss is the ratio between the sum of powers of all the returned pulses and the power of the incident pulse. The coding loss is a relevant factor in the system analysis since this directly affects the correlation and detection performance.

The MBG could be inserted directly in the data fiber without wavelength selector (WS) because it operates out of band. Note however, that this MBG could not be written with high reflectivity; only 40-60 % reflectivity was previously reported. The encoders of FIG. 21C and FIG 21E look very competitive in terms of cost and reflectivity.

System modeling

Let Ω be a collection of binary n-tuplets from the specification (n, w, λa, λc) where n is the code length, w is the Hamming weight, λ_a and λ_c are constraints defined as follows. For vectors $X, Y \in \Omega$, the expressions

$$R_X(\tau) = \sum_{i=1}^{n} X(i) X(i+\tau) \le \lambda_a$$

and

$$R_{XY}(\tau) = \sum_{i=1}^{n} X(i) Y(i+\tau) \le \lambda_c$$

define respectively the autocorrelation and the cross-correlation functions, both for $-n+1 \le \tau \le n-1$ and their constraints. Note that the code weight w (i.e., the number of logical ones per code) is equal to the number of delay lines in the encoding devices of FIG. 21B and 21D, and the number of Bragg gratings in the MBG encoder of FIG. 21E.

OOCs could never be made truly orthogonal, especially in an asynchronous case. The autocorrelation will generally be perturbed by interference coming from other branches. It is known that the performance of most OCDMA systems is limited by interference. However, in this application, the interference problem is much lower than that in traditional OCDMA system because: (i) the repetition rate of the incident monitoring pulse can easily be reduced, avoiding interference between reflections resulting from sequential pulses; (ii) the distance between customers will affect the interference statistics since only close customers will cause appreciable interference.

It is not the goal of the present invention to develop the methodology of dealing with interference rejection and detection threshold, but it is clear that the present system suffers less from interference problem, and requires an analysis different from traditional OCDMA. For instance, encoders do not transmit data, i.e., every pulse will contribute to an encoded signal without any modulation, i.e., the activity factor is always 1. In addition, the performance study of the present system should focus in the future on the probability of false alarm rather than the bit-error rate or the probability of error. This is as analysis method and tool unused in data communications OCDMA system.

Loss budget

Recall that the correlation process of the present invention uses the reflected power instead of the Rayleigh backscattered power, thus alleviating the dynamic range requirement compared to the standard OTDR system, by about 40 dB. Furthermore, the existence of an encoder, acting as a mirror at a fiber end increases the reflected power, thus additionally alleviating the required dynamic range. The decoder introduces an additional loss, but this remains quite limited compared to the gain we achieve in the dynamic range. The importance of the loss/power budget in the present system should be considered in a monitoring (or OTDR) context rather than in data communication context. OTDR and monitoring researchers usually use special photodetectors with extremely high photosensitivity and large dynamic rage. Commercial OTDRs currently work with received power that ranges from -90 to -100 dBm and supports a dynamic range of about 120 dB.

Capacity Analysis

For all of the three architectures exemplified above, the OCDM system is unchanged, only the capacity requirement changes. In this section we concentrate on the coding capabilities of a DS-OCDM system. We look to the key parameters that maximize the different optical orthogonal codes that could be assigned in our application.

Researchers recently developed an OOC generating technique, the so called Outer-product matrix based algorithm, that maximizes the number of codes for a given weight w, length n, and unit cross-correlation and auto-correlation side-lobes (λa=λc=1). We used this algorithm to develop a coding system. In FIG. 22A and 22B we show the number of codes (i.e., clients) versus code length n for different code weights w. From FIG. 22A, a designer could determine the appropriate (w, n) pairs to support EPON, GPON etc. For w=4, four delay lines are required, the encoder of FIG. 21(c) uses one 1:8 PS (i.e., 1:23 PS with q=2) and the MBG encoder of FIG. 21(e) requires four gratings. FIG. 22B presents codes that could support TDM/WDM-PON of FIG. 20B. In our analysis here we assumed the optical pulses sent from the monitoring unit were normalized in power and duration. More extensive analysis would include the detector sensitivity, the absolute pulse power and duration.

C. Applications with arbitrary dimension codes

All the applications described in the previous section could be addressed by mean of two dimensional codes (both time and wavelength) or wavelength only dimensional codes. This simply will require larger wavelength spectrum to be exploited for the monitoring. However, this could be very helpful to increase the signal to noise ratio, since more power is involved for coding, and/or increase the cardinality of the codes, repetition rate of the pulses, etc.

FIG. 23 shows a two dimensional (time and wavelength) OCM coding embodiment using a series of

Bragg gratings. Other known methods could be used to implement two dimensional coding, especially those previously proposed for optical fast frequency hopping CDMA (or two-dimensional OCDMA) etc. See for example Fathallah, H., L. A. Rusch and S. LaRochelle, "Fast Frequency Hopping Spread Spectrum for Code Division Multiple Access Communications Networks (FFH-CDMA)," Issued U.S. Patent No: 6.381.053, April 30, 2002, which is incorporated herein by reference.

FIG. 24 shows one wavelength-only dimension OCM coding embodiments using series of pass-band Bragg gratings. Other known methods could be used to implement wavelength-dimensional coding, especially those previously proposed for frequency encoded OCDMA (or spectral amplitude coding SAC-OCDMA) etc.

D. TDM-PON management challenges

In the following section, we provide a detailed description of numerous TDM-PON management challenges. These include problems related to OTDRs, FTTH installation, service provisioning, maintenance, and control/ownership demarcation (ultimately a demarcation of responsibility). We explain also how the OCDM system of the preferred embodiments of the present invention addresses all these issues and provides promising solutions.

Point-to-Multipoint problem

Standard OTDR based on Rayleigh backscattering and power reflections, used to monitor point-to-point links, are ineffective in point-to-multipoint TDM-PONs. Each branch termination connected to an optical network unit (ONT), as well as every splice, connector and fiber default or break, contributes to a reflection peak and/or power loss step, a so called event. The OTDR receiver observes the power that is the sum of Rayleigh backscattered and reflected light powers from all individual branches. As the number of branches in the network increases, the OTDR trace complexity increases proportionally. The network manager still has no efficient tools to recognize which event corresponds to which connector, splice, fusion or branch end. The management task is even more difficult when an observed peak event corresponds to simultaneous or close-in-time events in the network. Our OCDM encoders will introduce codes inside the reflected powers from every branch end, allowing the CO receiver to decode reflections from each branch separately. Identifying the code in a reflected train of pulses is the equivalent of identifying a specific branch.

OTDR dynamic range

Passive splitters with a high number of ports (32, 128 and recently 512) induce very high loss (15 dB, 21 dB and 27 dB), rapidly calling for much higher dynamic range in future OTDRs. It was previously recommended to use of a reflective element at every fiber end to increase the amount of power returning to the OTDR. This reduces the requirement of very high dynamic range since the OTDR receiver measures the reflected power to detect the end of a branch instead of the Rayleigh backscattering power that is typically tens of dBs lower (about -40 dB). In the present system, the OCDM encoder already performs this reflection role, in addition to introducing signatures inside the reflected power. Note also that the system and method herein consider the reflected powers only, in contrast to the standard OTDR that measures the reflected powers and the Rayleigh backscattered powers as well. This greatly alleviates the loss/power budget constraints of the system.

Limits of the ONT intelligence

In currently deployed FFTH networks, the ONTs are intelligent enough to cyclically communicate with the optical line terminal (OLT) at the CO. Status cells are exchanged almost every 100 ms to inform the network manager about the quality of the received signal at the ONT. When the quality of this signal degrades, the ONT information is not sufficient for the network manager to localize the origin of the degradation.

The quality of the signal delivered to the customer depends on three different independent elements: (i) the transmission quality at the central office, (ii) the fiber link quality and (iii) the receiver quality at the ONT (including detection and all signal processing steps). Constant communication between the OLT and the ONT is essential for the network manager to estimate the total quality of the transmission link and many other aspects. When the transmission quality degrades, it is not possible to localize the impairment, nor to determine if the impairment is due to (i), (ii) or (iii).

The network manager needs information about every segment of the network. Information about the OLT transmission quality is already available to the network manager through integrated tapped detection at the OLT laser. Information about the total quality of the system is available through direct communication between the OLT and the ONT. The missing information is that of the fiber link between the OLT and the ONT. Recall that the focus of this proposed solution, is to provide a technique for the network manager to obtain this missing information. Our technique allows the network manager to identify the faulty branch and to in-service monitor the total loss exhibited by any working fiber.

FTTH service provisioning

Fixing the RN to a customer’s distance: During FTTH installation, some of the OTDR suppliers recommend that no customers be connected to the remote node (RN) with equal length fibers. This recommendation is made to ensure that every network branch will contribute to a discrete, distinguishable event in the OTDR trace. Note that events coming from equidistant customers overlap in the OTDR trace and confuse the network manager. This installation criterion reduces the chance that equidistant events overlap in an OTDR trace, but it cannot guarantee that other reflection sources such as connectors, splices, fusions etc. will not cause ambiguity in the OTDR trace. Note that this recommendation is not a part of the FTTH standard. The use of simple OCDM encoders at the ends of the network branches allows multiple reflections to overlay in a pseudo-orthogonal way. The distance between the customers and the remote node is no longer an issue, and no longer need be controlled or determined in advance of installation, as recommended by various OTDR suppliers.

Unpredictable customer demand: Customer demand for FTTH services is unpredictable, thus the network ramification and distances to clients is unpredictable. The previous fiber length recommendation increases the complexity and the cost of provisioning new customers. This problem becomes even more evident when the number of branches in a TDM-PON increases. This increases the number of discrete and overlapping events in the CO OTDR trace, dramatically aggravating the task of the network manager.

Unused RN Ports: In typical PON roll-out, some unused capacity remains at the splitters, resulting in unused ports, as illustrated in Fig 1. The unconnected ports in the RN simultaneously reflect back a power and contribute to a high peak event that is an accumulation of many overlapping, indiscernible events. The OCDM encoders could be installed at the RN output ports, preventing the CO manager to be confused by the events occurring from the unused ports of the RN. When a new customer is connected to one port its specific encoder is removed and placed at the fiber end in the front of the customer ONT.

FTTH Maintenance

Fiber cut identification: When a fiber cut occurs at a distance that coincides or is close to an event of another branch, the CO manager will observe no event in the OTDR trace. For an isolated fiber break, a new peak event will be observed, but no indication that helps to determine the faulty branch. Extensive prior knowledge of all elements of the network could help the manager guess the nature of the event; however, this is an inefficient control of the network. Some OTDR suppliers propose that the network manager wait until receiving a call from the disconnected customer! If the number of customers claiming service interruption increases, the manager will understand that the fault occurred in the feeder instead of the distribution segment. This is intuitive, but provides no systematic solution to the PON management issues. In our system, when a fiber branch is cut, the monitoring equipment will miss the encoded signal that is specific to the cut branch. Note that when one customer calls for an interruption, the manager cannot determine if the problem is coming from the fiber or from the ONT itself. In that case, the OTDR suppliers recommend that a technician go to the customer premise and start testing by checking the ONT first. We will see in the end of this section how the OCDM passive encoding device delimits the service provider responsibility from that of the customer. In effect, the service provider has direct control and responsibility of the OLT and the fiber network, but the ONI is almost always under the customer control.

Quality of Service: The service provider cannot rely on customer calls to assure its quality of service. It is crucial for any telecom system to be able to guarantee a level of service that is defined by the number of interruption per year and the mean duration for these interruptions. Efficient monitoring requires automated fiber fault location and preventive in-service and live network measurements. In addition, customers will request Service Level Agreements with service providers to ensure an acceptable quality of service. Loopback information, including an estimate of the total loss, received end power, the ONT state, etc. is necessary to ensure adequate management of the network, etc. Our encoding system could be used to have an accurate estimate of the total loss exhibited through the network for every termination.

Demarcation point:

As shown in Fig. 16, the demarcation point is the location in a network where control (or sometimes ownership), and thus responsibility, switches from the service provider to the customer. The carrier maintenance responsibility starts from the central office and stops at these so called demarcation points. The demarcation point is adjacent to the customer premises, in the front of the ONT connector. The demarcation device could be installed outside the customer premise, thus accessible to the technicians without the customer presence. The customer controls (or sometimes owns), hence takes care of the ONT that is installed inside his premises or home (see Fig 16.). When no communications exists between the CO and the ONT, the manager cannot determine if this is caused by a fiber cut that is his maintenance responsibility, or if simply the ONT is disconnected or turned OFF, which is the customer responsibility. PONs need a device, preferably passive, to be installed at every ONT, outside the premises, and that identifies exactly the demarcation point for that branch. We will see in the following section how our OCDM encoder fulfills this need and serves as the demarcation point device.

Numerous modifications could be made to the embodiments above without departing from the scope of the present invention.

We claim::

1. A method for testing an optical network for defects between a network node and a plurality of network locations, each network location being connected to the network node through a corresponding light path, said method includes the steps of:

a) transmitting a pulsed monitoring light signal from the network node to each of the network locations through the corresponding light path;
b) providing an encoder in each of the light paths proximate the corresponding network location, each encoder reflecting the monitoring signal back towards the network node and encoding the reflected monitoring light signal according to an encoding function, the encoding function of each encoder having a low cross-correlation to the encoding function of all other encoders;
c) receiving a return signal at the network node corresponding to the reflection of the monitoring light signal in said light paths; and
d) for at least one of said light paths:
   - decoding the return signal according to a decoding function correlated to the encoding function associated with said light path, thereby obtaining a decoded return signal; and
   - analysing the decoded return signal to determine therefrom if any defect is present in said light path.

2. The method according to claim 1, wherein the encoding of step b) comprises modifying at least one of a temporal modulation, a wavelength, a phase and a

polarisation of the monitoring light signal.

3. The method according to claim 1, wherein the decoding of step d)i is performed optically.

4. The method according to claim 1, wherein the decoding of step d)i is performed electronically.

5. The method according to claim 1, wherein, if a defect is determined to be present, the analysing of step d)ii further comprises estimating a location of said defect along the light path.

6. The method according to claim 1, wherein the analysing of step d)ii comprises searching the decoded return signal for an autocorrelation major peak corresponding to a position of the encoder along said light path, and identifying said light path as broken if said autocorrelation major peak is not located.

7. The method according to claim 6, wherein, if said autocorrelation major peak is located, the analysing of step d)ii comprises searching the decoded return signal for at least one reflection peak, and, if detected, interpreting each of said at least one reflection peak as a potential defect along said light path.

8. The method according to claim 6, wherein the decoding of step d)i is performed electronically, and the analysing of step d)ii comprises, if said autocorrelation major peak is not located:

- extracting a transfer function from said decoded return signal, said extracting comprising using at least one of information from a decoding of all other light paths is said optical network, and information from a previous testing of said optical network; and
- searching the transfer function for a reflection peak corresponding to a break along said light path, and if detected, using said reflection peak to estimate a location of the break along the light path.

9. The method according to claim 1, wherein the monitoring light signal transmitted at step a) is modulated according to a pseudo noise technique.

10. A system for testing an optical network for defects between a network node and a plurality of network locations, each network location being connected to the network node through a corresponding light path, said system comprising:

- transmitting means for transmitting a pulsed monitoring light signal from the network node to each of the network locations through the corresponding light path;
- an encoder associated with each of the light paths and provided therein proximate the corresponding network location, each encoder reflecting the monitoring signal back towards the network node and encoding the reflected monitoring light signal according to an encoding function, the encoding function of each encoder having a low cross-correlation to the encoding function of all other encoders;
- receiving means for receiving a return signal at the network node corresponding to the reflection of the monitoring light signal in said light paths;
- decoding means for decoding the return signal according to any one of a plurality of decoding functions, thereby obtaining a decoded return signal, each decoding function being correlated to the encoding function associated with one of the light paths; and
- analysing means for analysing the decoded return signal to determine therefrom if any defect is present in the light path associated with the corresponding decoding function.

11. The system according to claim 10, wherein the transmitting means comprise a light source generating the pulsed monitoring light signal, said pulsed monitoring light signal having a low frequency rate and a monitoring wavelength.

12. The system according to claim 11 adapted for use in a WDM optical network having at least one WDM demultiplexer connecting an input branch to multiple output branches, wherein the system comprises, for each demultiplexer of the optical network, a bi-directional bypass assembly coupling the monitoring signal between the input branch and each of the output branches.

13. The system according to claim 11, wherein each of the encoders comprises a passive device fragmenting the monitoring signal into a predetermined number of sub-pulses distributed in time according to the corresponding encoding function.

14. The system according to claim 13, wherein each of the encoders comprises a resonant cavity dividing the monitoring signal into said sub-pulses, a path length within said resonant cavity being different for each of the encoders.

15. The system according to claim 10, wherein the decoding means comprise a plurality of optical decoders, each decoder reflecting the return signal according to one of the plurality of decoding functions, and an optical switch for directing the return signal to any one of said optical decoders.

16. The system according to claim 10, wherein:

- the receiving means comprise a detector for detecting the return signal, thereby obtaining an electronic return signal; and
- the decoding means and analysing means are integral to a processor connected to the detector for receiving the electronic return signal therefrom.
- 17. The system according to claim 16, wherein the processor comprises:
- a decoding application for parallely decoding the electronic return signal according to each of the decoding functions, thereby electronically obtaining the decoded return signal for each of the light paths; and
- a correlation application searching each of the decoded return signal for an autocorrelation major peak corresponding to a position of the encoder along the corresponding light path, and identifying said corresponding light path as broken if said autocorrelation major peak is not located.

18. The system according to claim 17, wherein said correlating application is adapted to, when said autocorrelation major peak is not located, extract a transfer function from said decoded return signal, using at least one of information from a decoding of all other light paths is said optical network, and information from a previous testing of said optical network, and search the transfer function for a reflection peak corresponding to a break along said light path, and if detected, using said

relfection peak to estimate a location of the break along the light path.

19. A set of devices for installation in an optical network for testing the same for defects between a network node and a plurality of network locations, each network location being connected to the network node through a corresponding light path, said comprising:

- a light generating module for generating a pulsed monitoring light signal, said light generating module having a light output connectable to said optical network for transmitting the monitoring light signal from the network node to each of the network locations through the corresponding light path;
- a plurality of encoders each connectable to one of the light paths proximate the corresponding network location for reflecting the monitoring signal back towards the network node, each encoder having an encoding function for encoding the reflected monitoring light signal, the encoding function of each encoder having a low cross-correlation to the encoding function of all other encoders;
- a processing module having a light input for receiving a return signal at the network node corresponding to the reflection of the monitoring light signal in said light paths, said processing module having decoding means for decoding the return signal according to any one of a plurality of decoding functions, thereby obtaining a decoded return signal, each decoding function being correlated to the encoding function associated with one of the light paths, and analysing means for analysing the decoded return signal to determine therefrom if any defect is present in the light path associated with the corresponding decoding function.

20. The set of devices according to claim 19, wherein each of the encoders comprises a passive device fragmenting the monitoring signal into a predetermined number of sub-pulses distributed in time according to the corresponding encoding function.

21. The set of devices according to claim 20, wherein each of the encoders comprises a resonant cavity dividing the monitoring signal into said sub-pulses, a path length within said resonant cavity being different for each of the encoders.

23. The set of devices according to claim 19, wherein the processing module comprises:

- a detector for detecting the return signal, thereby obtaining an electronic return signal; and
- a processor integrating the decoding means and analysing means, the processor being connected to the detector for receiving the electronic return signal therefrom.

23. The set of devices according to claim 22, wherein the processor comprises:

- a decoding application for parallelly decoding the electronic return signal according to each of the decoding functions, thereby electronically obtaining the decoded return signal for each of the light paths; and
- an correlation application searching each of the decoded return signal for an autocorrelation major peak corresponding to a position of the encoder along the corresponding light path, and identifying said corresponding light path as broken if said autocorrelation major peak is not located.

24. The set of devices according to claim 23, wherein said correlation application is adapted to, when said autocorrelation major peak is not located, extract a transfer function from said decoded return signal, using at least one of information from a decoding of all other light paths is said optical network, and information from a previous testing of said optical network, and search the transfer function for a reflection peak corresponding to a break along said light path, and if detected, using said relfection peak to estimate a location of the break along the light path.

ABSTRACT

A method and system for testing an optical network for defects in multiple light paths are presented. A pulsed monitoring light signal is transmitted in the network, and reflected by encoders in each light path. The encoders encode the light signal according to encoding functions having a low cross-correlation to each other. The return light signal from all light paths is decoded, either optically or electronically, according to decoding functions correlated to each of the encoding functions, and analysed to determine if a defect is present in any given light path. According to some embodiments, the location of the defect along the light path may also be determined.