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Optical Power Budget and Cost Analysis in PON-based *i*-FTTH

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Abstract: This study focuses on the performance evaluations in 8-branched Passive Optical Network (PON)-based Intelligent Fiber-To-the-Home (*i*-FTTH). We calculate the optical power budget and margin when design a conventional PON-based FTTH and proposed PON-based *i*-FTTH with different link length and splitting ratio of 1x*N* passive optical splitter. A simple calculation is used to determine how much loss and power are available for each fiber link in both networks with different type of signals. The cost estimation for both networks including the additional optical monitoring, switching and protection systems are calculated and compared.

Key words: PON, *i*-FTTH, power margin, link length, splitting ratio

INTRODUCTION

PON is one among several architectures that can be used in fiber-to-the-home (FTTH). PON has been early described for FTTH as early as 1986. PON-based FTTH is today the main choice of many Network Services Providers (NSPs) since it breaks through the economic barrier of traditional Point-to-Point (P2P) solutions. PON-based FTTH provides a powerful Point-to-Multipoint (P2MP) solution to satisfy the increasing demand in the access part of the communication infrastructures between Central Office (CO) and customers sides (Skubic *et al*., 2009). PON is a technology viewed by many as an attractive solution to the first mile problem; a PON minimizes the number of optical transceivers, CO terminations and fiber deployment. A PON-based FTTH is a P2MP optical network with no active elements in the signal path from source to destination. The only interior elements used in a PON-based FTTH are passive optical components, such as optical fiber, splices and splitters. A PON-based FTTH employs a passive device (i.e., optical splitter/branching device, etc., that not requiring any power) to split an optical signal signals from multiple fibers into one. PON-based FTTH is capable of delivering triple-play (data, voice and voice) services at long reach up to 20 km between CO and customer sides. All transmission in a PON-based FTTH is performed between an Optical Line Terminal (OLT) and optical network units (ONUs). OLT resides at CO; while ONU is located at the end-user location (Mukherjee, 2006).

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Nowadays, PON-based FTTH s commonly deployed as it can offer a cost-efficient and scalable solution to provide huge-capacity optical access (Prat, 2007). The cost effectiveness of PON-based FTTH depends on numbers of ONUs per OLT optical transceiver, the cost of fiber and its installation, the cost of the Digital Subscriber Line (DSL) transceivers at ONU and subscriber premise equipments, the overall cost of powering ONU and the real estate cost of placing the ONU (Gorshe, 2006). Fixed network and exchange costs are shared among all subscribers. This reduces the key cost per subscriber metric. The PON solution benefits from having no outside-plant electronic to reduce the network complexity and life-cycle costs, while improving the reliability of FTTH (Corning, 2005).

The introduction of PON-based FTTH allows the network to transport huge amounts of data and provide communication services that play a very important role in many of our daily social and economical activities. Network reliability is an issue of deep concern to network operators being eager to deploy high capacity fiber networks, since a single failure in the network could result in significant losses of revenue. The importance of network reliability will keep pace with the steadily increasing network capacity. For very-high-capacity future optical networks, carrying multitudes of 10 Gbps channels per fiber strand, a failure of optical connection will interrupt a vast amount of services running on-line, making the connection availability a factor of great significance (Wosinska *et al.*, 2009).

Troubleshooting a PON-based FTTH involves locating and identifying the source of an optical problem in what may be a complex optical network topology that includes several OLT, optical splitter, fibers and ONUs. Since, most components in the network are passive, a large part of the issues are due to dirty/damaged/misaligned connectors or breaks/macrobends in the optical fiber cables. These will affect one, some or all subscribers on the network, depending on the location of the problem. If fiber breakdown/cut occurs in the feeder region (from OLT to optical splitter), all downstream signals toward ONUs will be affected. However, if a problem such as macrobending or dirty connector causes optical power to be lost somewhere in the network, only a number of ONUs may be affected. Since the attenuation in optical fiber cables is proportional to length, distant ONUs received a weaker downstream signal than closer ones. The upstream signals received at CO from more distant ONUs are also weaker and the OLT will detect such decreased performance (EXFO, 2000).

In order to facilitate effective and prompt network protection and restoration, it is highly desirable to perform network survivability measures in the optical layer. This can be achieved by simple fiber link or equipment duplication with protection switching or some other intelligent schemes with minimal resource duplication or reservation for protection. For PON applications, equipment failure at either OLT or ONU can be easily remedied by having a backup unit in the controlled environment. However, for any fiber cut, it would take a relatively long time to perform the repair. Therefore, it is highly desirable to have survivable PON architectures with protection switching against any fiber cut survivability (Chan *et al.*, 1999).

INTELLIGENT FIBER-TO-THE-HOME (*i*-FTTH)

i-FTTH is an improved PON-based FTTH network system associated with centralized monitoring, failure troubleshooting, protection switching and automatic recovery features. The system design of *i*-FTTH consists of 5 major elements, which are: (1) Centralized Failure Detection System (CFDS), (2) Smart Access Network_Testing, Analyzing and Database (SANTAD), (3) Access Control System (ACS), (4) Multi Access Detection System (MADS)

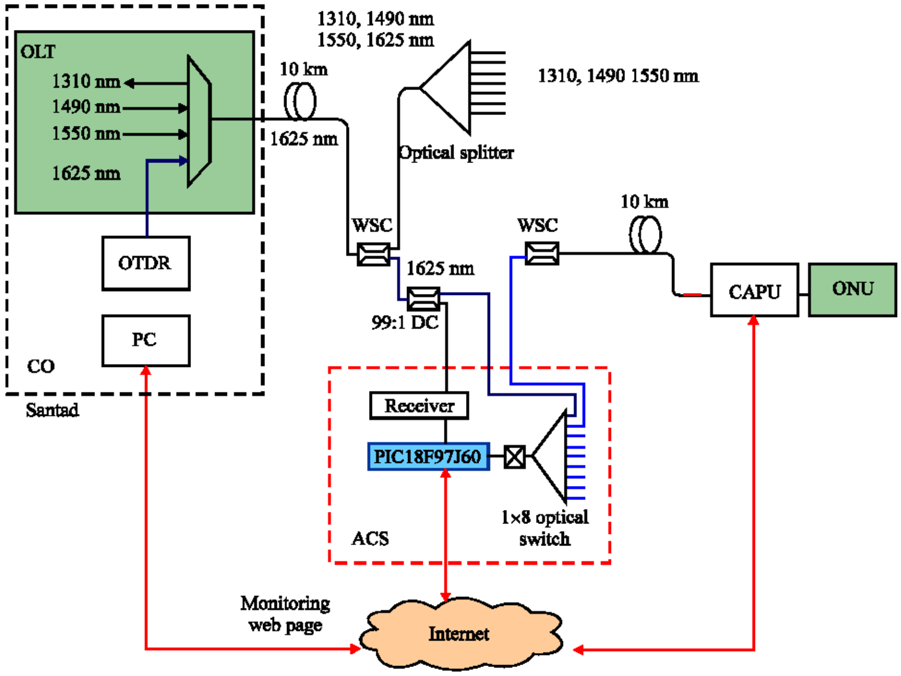

Fig. 1: Schematic diagram of PON-based Intelligent Fiber-To-the-Home (*i*-FTTH)

and (5) Customer Access Protection Unit (CAPU) as shown in Fig. 1. MADS taps 10% of 1550 nm video signal at drop section to firstly detect the faulty line and the exact failure location will be determined by SANTAD. CFDS and SANTAD are integrated with Optical Time Domain Reflectometry (OTDR) for centralized monitoring and troubleshooting any degradation or fault that occurs in PON-based *i*-FTTH downwardly from CO towards customer residential locations (in downstream direction).

CAPU is an Optical Programmable Switch Device (OPSD) implemented at the end-users side just before ONU to perform self restoration against fiber failures. It comprises of 1×2 and 2×2 optical switches as well as a microcontroller system. ACS is located at middle of the network system for controlling CAPUs and responsible to route the 1625 nm OTDR signal to each corresponding drop fiber to enable them be monitored from CO. Any failure/breakdown occurs in the network system will be restored by switching the distributed signals to protection line by CAPU that coupled with asymmetric digital subscriber line (ADSL) copper wire from CO through ACS. In case of both working line and protection line are failure, the traffic can be recovered by using neighbor line.

OPTICAL POWER BUDGET AND MARGIN CALCULATION

The key to network distance is optical power budget: the amount of light available to make a fiber optic connection. Optical loss or total attenuation is the sum of the losses of each individual component between a transmitter and receiver including fiber, splices, couplers and other optical devices. The loss is relative to the transmitter output power and affects the required receiver input power. Loss budget calculation analysis is the calculation and verification of a fiber optic system's operating characteristics. Transmitter launch level power, receiver sensitivity and the dynamic range are crucial number used in span analysis. The overall span loss or link budget can be determined using an optical power meter to measure the true loss or by computing the loss of system components. Typically, the safety margin sets aside 3 dB. This number will be different for every organization depending on how much risk they want to assume in their network. To guarantee error free operation, a value no less than 1.7 dB should be used. This safety factor is subtracted from the remaining power from above. If the number is still positive after all of this, you can be assured that your fiber network will deliver the required performance over the life of the installation (Transition Networks, 1999).

Power at a particular wavelength generated by the transmitter Light Emitting Diode (LED) or Laser Diode (LD) used to launch the signal is known as the transmitter launch level. Receiver sensitivity and dynamic range are the minimum acceptable value of received power needed to achieve an acceptable Bit Error Rate (BER) or performance. Receivers have to cope with optical inputs as high as -5 dBm and as low as -30 dBm, the receiver needs an optical dynamic range of 25 dB. To ensure that the fiber system has sufficient power for correct operation, a span's power budget, which is the maximum amount of power it can transmit, is calculated. From a design perspective, worst case analysis calls for assuming minimum transmitter power and minimum receiver sensitivity. This provides for a margin that compensates for variations of transmitter power and receiver sensitivity levels. With minimum transmit power and minimum receive sensitivity data, we can now calculate the available light. Factors that can cause span or link loss include fiber attenuation, splice loss, connector loss, chromatic dispersion and other linear and non-linear losses. Power margin, P_M, represents the amount of power available after subtracting linear and non linear span losses from the power budget.

$$\text{Power budget } (P_B) = \text{Minimum transmitter power } (P_{TMIN})\text{-Minimum receiver sensitivity } (P_{RMIN}) \tag{1}$$

$$\text{Link margin } (P_S) = (\text{Fiber attenuation} \times \text{km}) + (\text{splice loss} \times \text{No. of splices}) + (\text{connector loss} \times \text{No. of connectors}) \tag{2}$$

$$\text{Power margin } (P_M) = \text{Power budget } (P_B)\text{-link margin } (P_S)\text{-safety margin} \tag{3}$$

Fiber link loss measurements must be carried out using a laser source and a power meter in both directions on each fiber span to ensure that the actual link loss is less than the budgeted loss. One of the most important parts of preparing a high speed transmission network is developing and adhering to fiber cleanliness standards. Dirty optical connectors are the main cause of failures over time. Furthermore, they contribute to Optical Return Loss (ORL), which may increase noise and result in higher Bit Error Rate (BER) (Andrews, 2009).

Optical Power Budget and Margin Calculations for Conventional Pon-Based Ftth

In this design, the minimum transmitter power and minimum receiver sensitivity is set as 0 and -34 dBm. The available power or power budget for the designed architecture is 34 dBm and the dynamic range is 31 dBm with safety margin 3 dBm. The available splitting ratios of 1×N passive optical splitter are 1×4, 1×8, 1×16, 1×32, 1×64 and 1×128. Commercial PON-based FTTH network systems commonly use the 1×16 or 1×32 splitting ratio. The splitting ratio affects the power budget in PON-based FTTH network system. A higher splitting ratio means that the cost of OLT is better share among ONUs and the OLT bandwidth is shared among more ONUs thus less bandwidth per user.

Table 1: Theoretical loss for 1xN optical splitter

Splitting ratio	No. of users	Power per user (%)	Loss calculation (dB)	Insertion loss (dB)
1:2	2	50.00	-3.01	-3
1:4	4	25.00	-6.02	-6
1:8	8	12.50	-9.03	-9
1:16	16	6.25	-12.04	-12
1:32	32	3.13	-15.04	-15
1:64	64	1.56	-18.07	-18
1:128	128	0.78	-21.08	-21

Table 2: Link margin and power margin for 1:8 splitting ratio

	Link margin (dBm)			Power margin (dBm)		
Line	1310 nm	1490 nm	1550 nm	1310 nm	1490 nm	1550 nm
1	15.83	13.68	12.90	15.18	17.32	18.10
2	15.48	13.44	12.70	15.53	17.56	18.30
3	14.95	13.08	12.40	16.05	17.92	18.60
4	14.08	12.48	11.90	16.93	18.52	19.10
5	14.95	13.08	12.40	16.05	17.92	18.60
6	13.73	12.24	11.70	17.28	18.76	19.30
Average	14.84	13.00	12.33	16.17	18.00	18.67

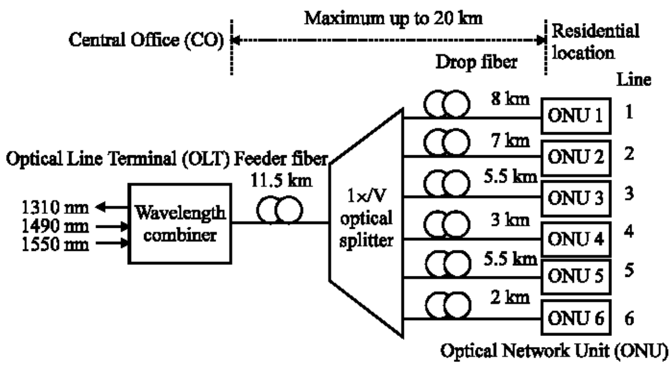

Fig. 2: Schematic diagram for conventional PON-based FTTH

Loss is one of the main concerns and any extra loss in power directly brings in reduction of number of subscribers to NSPs. This becomes a permanent loss to the NSPs (Varghese and Nair, 2009). Table 1 lists the theoretical loss for 1×N optical splitter. Table 2 shows the link margin and power margin for each transmission line in the conventional PON-based FTTH as shown in shown in Fig. 2. The link margin for triple-play signals will increase by 3 dB as the splitting ratio of 1×N optical splitter increases twice. The average power budget, power margin and dynamic range of each fiber link are summarized in Fig. 3.

Optical Power Budget and Margin Calculations for Proposed PON-based *i*-FTTH

In this design, a 1×N optical splitter is used to broadcast the triple-play signals from one fiber (feeder fiber) to many fibers (drop fibers) at remote node (RN), where each ONU at the customer side will be connected to main line and protection line. In other word, a 1×N optical splitter is accommodated to N/2 users in the proposed PON-based *i*-FTTH. Table 3 shows the link margin and power margin for each fiber link in PON-based *i*-FTTH as shown in shown in Fig. 1. The link margin for triple-play signals will increase by 3 dB as the splitting ratio of 1×N optical splitter increases twice, but the link margin and power margin for 1625 nm signal is maintain at the same level because this signal is routed into a tapper circuit to

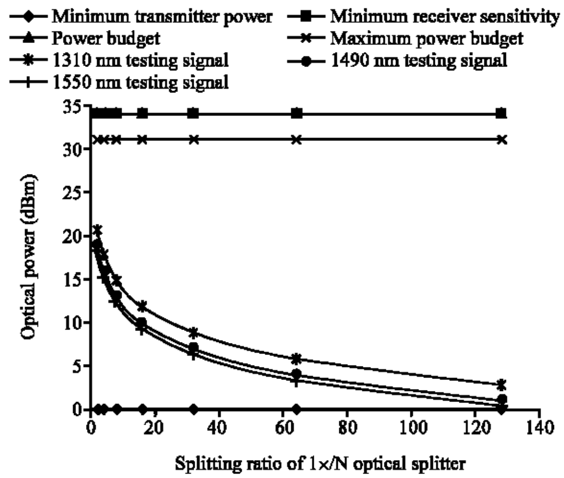

Fig. 3: Average optical power budget for each optical line in conventional PON-based FTTH

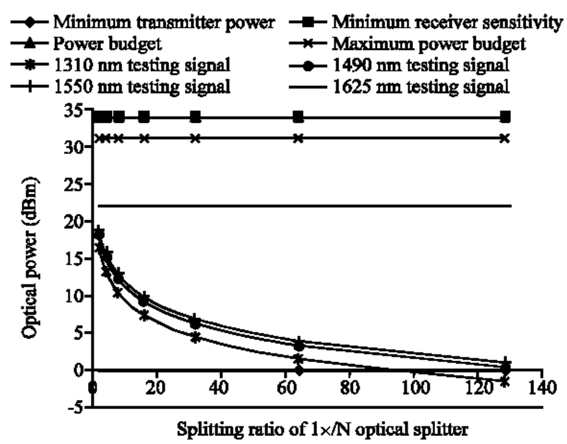

Fig. 4: Average optical power budget for each optical line in proposed PON-based *i*-FTTH

Table 3: Link margin and power margin for 1:8 splitting ratio

	Link margin (dBm)				Power margin (dBm)			
Line	1310 nm	1490 nm	1550 nm	1625 nm	1310 nm	1490 nm	1550 nm	1625 nm
1	19.67	17.52	16.74	8.19	11.34	13.48	14.26	22.82
2	21.79	19.86	19.16	10.55	9.22	11.14	11.84	20.46
3	18.79	16.92	16.24	7.61	12.21	14.08	14.76	23.39
4	23.74	22.14	21.56	9.86	7.27	8.86	9.44	21.15
5	18.90	17.03	16.35	7.72	12.10	13.97	14.65	23.28
6	20.50	19.01	18.47	9.74	10.51	11.99	12.53	21.27
Average	20.57	18.75	18.09	8.95	10.44	12.25	12.91	22.06

bypass the optical splitter in conventional PON-based FTTH. The average power budget, power margin and dynamic range of each fiber link are summarized in Fig. 4. A 1:128 splitting ratio is not suitable to be applied in PON-based *i*-FTTH because the power margin for triple-play signals is less than 0 dBm.

LOSS MEASUREMENT

The insertion loss for each component used in conventional PON-based FTTH and proposed PON-based *i*-FTTH is listed in Table 4. The average exact measured optical power, power budget and dynamic range of each transmission line in conventional PON-based FTTH and proposed PON-based *i*-FTTH with different splitting ratio are summarized in Table 5 as well as Fig. 5 and 6. The average exact optical power or total system loss is determined by using an optical power meter (for 1310, 1490 and 1550 nm) and OTDR (for 1625 nm).

The two most common tools used for fiber optic cable testing are optical power meter and OTDR. Both can measure attenuation (signal loss) on a fiber optic link, yet they usually

Table 4: Insertion loss of each component

Optical components/devices/elements	Insertion loss (dBm) 1310 nm	1490 nm	1550 nm	1625 nm
1 m patch cord with FC connector	1.53	1.14	0.47	-
3 m patch cord with FC connector	1.44	-0.23	0.37	-
FC/FC adapter	-49.09	-46.47	-47.77	-
SMF-28 optical fiber (per km)	0.35	0.24	0.20	0.195
1x8 single mode PLC splitter	9.45	10.87	10.25	10.396
Customized Wavelength Selective Coupler (WSC)	0.63	0.63	0.63	0.49
Access Control System (ACS)	1.49	3.13	2.52	3.407
Customer Access Protection Unit (CAPU)	0.68	-1.62	-0.82	-

Table 5: Loss measurement in both networks with 1:8 splitting ratio

Line	Conventional PON-based FTTH 1310 nm	1490 nm	1550 nm	Proposed PON-based I-FTTH 1310 nm	1490 nm	1550 nm	1625 nm
1	15.97	15.16	14.01	19.65	20.53	18.49	6.94
2	16.06	15.43	13.83	19.60	20.71	18.89	7.39
3	15.46	15.26	14.44	17.93	19.46	17.99	6.10
4	14.50	14.19	13.20	18.61	20.07	18.19	6.37
5	14.92	14.67	13.11	19.69	20.85	19.23	6.62
6	13.91	13.79	12.90	17.84	19.78	17.81	5.85
Average	15.14	14.75	13.58	18.89	20.23	18.43	6.55

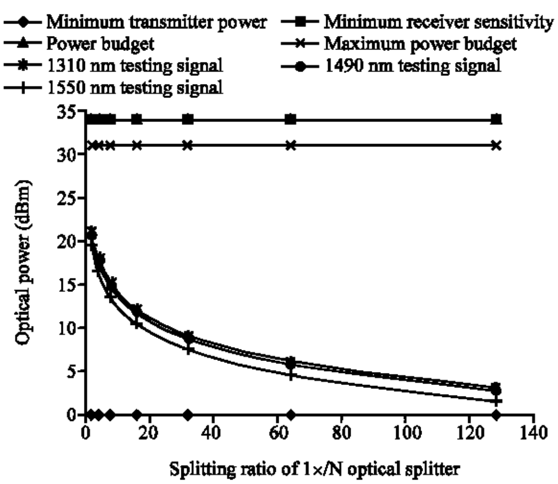

Fig. 5: Average measured optical power for each optical line in conventional PON-based FTTH

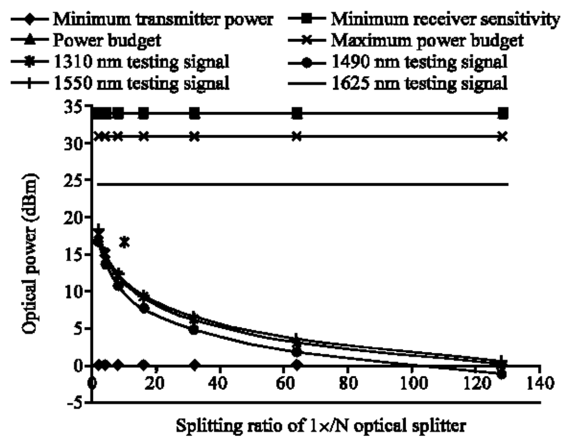

Fig. 6: Average measured optical power for each optical line in PON-based *i*-FTTH

provide different results. When a power meter and a light source are used to measure the loss in a fiber optic link, they closely model what the final installed equipment will do. A signal is sent from one end (source) to the other end (receiver or power meter) and power lost in the link due to attenuation is measured. However, an OTDR works on a completely different principle. There are a few reasons OTDR provides a significant difference from power meter when loss is measured on single mode fiber optic links. These differences include backscatter versus through measurements, receiver saturation, trace interpretation, launch cables and far-end connectors (Johnston, 1999).

FIBER INSPECTION

Fiber optic communication is achieved by transmitting a beam of light down an optical fiber cable. Dirty, dust and other particles on fiber end faces are the primary causes of troubleshooting in optical network. fiber. Typical fiber optic cores (signal carrying portion) are 9 μm for single mode and 62.5 μm for multimode. This makes cleanliness of optical connections extremely important. Common contaminates such as dust, dirt, oils, etc. may be larger than 9 μm and can attenuate or completely block an optical signal much like dirt attenuates visible light transmitted through windows. Many optical networks have tight loss budgets. Dirty connectors can quickly exceed the allowed loss. Dirty connectors are a common cause of costly down time for networks.

A few of the common connector contaminates are listed below:

Dust/Dirt

Dust and dirt are a fact of life. There are always particles airborne and on surfaces. Slight air currents can transport them to exposed fiber optic connectors.

Metallic Particles

Connector bodies are fiber housings are commonly made from plated metal (especially military connectors). Normal wear and tear will scrape off the platting in tiny particles. Normal wear and tear of hand tools can also produce tiny metal particles. Metal particles are similar to dirt with two exceptions:

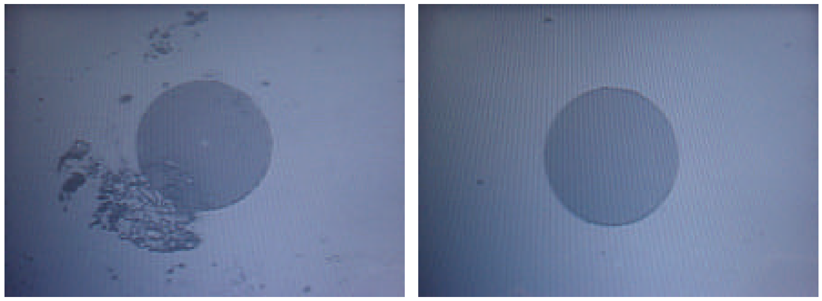

Fig. 7: Surface of fiber connector in fiber probe viewer. (a) Surface of dirty connector and (b) Surface of clean connector

Table 6: Loss comparison for 1 m patch cord and 2 km optical fiber with clean and dirty connectors

	1 m patch cord		2 km optical fiber line	
Laser source (nm)	Dirty connector (dBm)	Clean connector (dBm)	Dirty connector (dBm)	Clean Connector (dBm)
1310	-1.44	1.44	0.59	0.54
1490	-0.20	-0.18	-1.19	-1.08
1550	-0.41	0.42	-0.57	-0.42

Table 7: Loss comparison for 2 km optical fiber line with different modulation sources

Modulation	1310 nm (dBm)	1490 nm (dBm)	1550 nm (dBm)
270 Hz	-1.77	-3.37	-3.08
1 kHz	-1.73	-3.33	-2.71
2 kHz	-1.71	-3.29	-2.69
High	1.17	-0.48	0.15
CW (continuous wave)	-1.76	-3.46	-2.79
Auto ID	-1.81	-3.41	-2.82

- A charged connector (easily produced by dry wiping) is a magnet for metallic particles. They will literally jump to an electro-statically charged connector
- Metallic particles are by nature abrasive. Dry wiping can cause the fiber end to be scratched and damaged by metallic particles

Oils

Human skin is naturally oily. Contact with an optical connector virtually guarantees instant contamination of the connector end face (AFL Telecommunications, 2008).

Proactively inspecting and cleaning fiber connectors, enables field engineers and technicians to reduce network troubleshooting and downtime, optimizes signal performance and prevents network damage. A fiber inspection probe (FIP) is used to inspect both male (patch cord) and female (bulkhead) sides of a fiber interconnect (JDSU Uniphase Corporation, 2008). Cleaning connectors is quick and inexpensive since network downtime and service calls are costly. It is a good practice to clean and inspect connectors each time they are disconnected (AFL Telecommunications, 2008). A patch cord cable and optical fiber line composed of 1 and 2 km length, respectively, with clean and dirty connectors are inspected with a FIP and showed in fiber probe viewer (Fig. 7a, b). Figure 7b shows the view of dirty connector after cleaned by using fiber cleaner. The effect of clean and dirty connectors to optical signal level is listed in Table 6 and 7.

COST ESTIMATIONS FOR PON-BASED *i*-FTTH DEVELOPMENT

This section measures and compares the development cost of additional optical monitoring, switching and protection systems for PON-based *i*-FTTH with different splitting ratio in order to select the most cost efficiency configuration. The main development cost of conventional PON can be broadly divided in 2 categories, namely labor cost and electronic equipments. The labor necessary to deploy the Outside Plant (OSP) includes the cable, ducts and civil work represents the biggest piece of conventional PON-based FTTH first-installed cost. Labor costs come in two parts: the time to deploy, test and troubleshoot and the hourly rate of the installer. That hourly rate depends on the skill set and equipment required to install the components. The active electronic equipments in CO or Head End (HE) and at customer premises, where the equipment is shared among multiple subscribers and no active components are deployed in the field. The remaining is the passive components installed in the CO or HE as well as OSP (Mazzali, 2004). NSPs need to keep capital and operational expenditures (CAPEX and OPEX) low in order to be able to offer economical solutions for the customers. A full protection offers relatively high connection availability but unfortunately it requires duplication of all network resources and investment cost to realize the protection, which may result in CAPEX that is too high for the cost-sensitive access networks (Wosinska *et al*., 2007).

This study only considers the active electronic equipments and passive components in CO or HE, OSP and customers' sides. Figure 8 and Table 8 compare the cost estimation for developing conventional PON-based FTTH and proposed PON-based *i*-FTTH including SANTAD, ACS and CAPU. From this comparison, the development costs of conventional

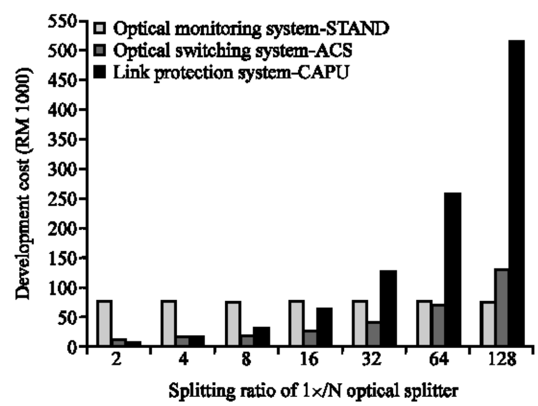

Fig. 8: Cost comparison between SANTAD, ACS and CAPU

Table 8: Cost estimations for both networks

	Developing cost (Ringgit Malaysia 1000)		
Splitting ratio	Conventional PON-based FTTH	Proposed PON-based i-FTTH	Value-add features
1:2	82.04	193.81	98.90
1:4	94.91	229.49	108.82
1:8	120.67	300.84	128.67
1:16	172.17	443.54	168.37
1:32	275.17	728.95	247.77
1:64	481.18	1,153.44	406.57
1:128	746.87	2,109.82	724.17

PON-based FTTH will increase when the splitting ratio of 1×N optical splitter increases twice because the number of users is increasing and excessive use of fibers as well as other optical devices in the drop section. The development costs of SANTAD, ACS and CAPU in proposed PON-based *i*-FTTH is increasing as well due to excessive use of additional optical components and devices such as optical switches, customized wavelength selective couplers (WSCs), microcontroller system, etc. This concludes the most cost-effective way is using the 1×64 configuration to minimize the development cost of PON-based *i*-FTTH.

CONCLUSION

This study has shown a new in-service monitoring and protection scheme for PON namely *i*-FTTH. The proposed PON-based *i*-FTTH is able to provide surveillance and protection features to avoid redundancy of fibers and equipments in conventional PON-based FTTH. The most cost-effective way is using the 1×64 configuration to minimize the development cost of PON-based *i*-FTTH.

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