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A GIS-based novel active monitoring system for fiber networks

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Abstract: In this study, a geographic information system (GIS)-based novel fiber network monitoring system has been developed to improve the operation and maintenance of fiber optic networks (FONs). The main aim of the developed system is to provide the required capabilities for both detailed digital modeling and central monitoring of FONs. The system can perform scheduled measurements and dispatch alarms if any fault or degradation is detected in the concerned FON. It also indicates the alarm locations on a map as a considerable contribution to decreasing mean time to repair. The developed monitoring system has more security features than others.

Key words: Fiber networks, monitoring system, optimization, optical time domain reflectometer, remote test unit

1. Introduction

Due to their high bandwidth, fiber optical networks (FONs) are increasingly employed in telecommunication infrastructures all over the world [1]. In recent years, even home users have access to fiber networks [2]. Risks of security and quality of service (QoS) constraints are a serious problem not only for copper or wireless communication technologies, but also for FONs [3].

There are various types of attacks, either for intrusion or in order to prevent communications over FONs. On the other hand, there may be problems with communications due to accidental damage of the fiber optic cables (FOCs). Although problems with communication channels are an important issue for civil applications such as service providers, threats to the security of communications are considerably higher in military and governmental applications [4].

As technology evolves, QoS becomes more important and end users become more willing to sign up for service level agreements (SLAs), which provide well-defined and measurable QoS parameters. Due to the tight constraints imposed by SLAs, maintenance of the FONs with optimized service and the estimation of the value loss caused by network breakdowns should be carefully considered [5].

Minimizing the mean time to repair (MTTR) is the main advantage of the developed fiber network monitoring system (FNMS). It is composed of FOC test equipment that is continuously monitoring the target network and the related management software. The FNMS allows the identification of problems such as aging, increased splice/connector loss, etc. High bit error rate (BER) and low network performance play key roles in low MTTR and QoS [6].

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Another typical capability expected from a FNMS is geographic information system (GIS)-integrated inventory management of a FON, because maintenance of up-to-date data related to a fiber optic infrastructure that is frequently changed is important for coherent administration [7]. If all stakeholders in an optical network are able to see a current and common centralized model of the network in order to perform their tasks, the time and cost required for management will be reduced significantly [8].

It is possible to summarize the benefits of employing a FNMS as follows:

- Problems such as cable aging and high splice/connector loss during the network deployment phase can be identified and solved in advance [9].
- Network availability can be increased/improved by identifying cable breakdown locations quickly, thus minimizing MTTR [10].
- QoS can be increased with minimized MTTR, and management of SLA can be eased with automatically generated fault statistics reports [11].
- Work load of the network administrators can be decreased with automated test configurations and warnings in various formats (voice, e-mail, SMS, etc.)
- Network security level can be increased with the detection of intrusions/hostile activities such as tapping [12].
- Networks can be managed more efficiently by associating FON information and alarm locations with geographical coordinates in a geographic view of the network [12].
- Effort and cost of network documentation can be decreased with easy sharing, reporting, and update features by modeling a network in a digital environment.
- Technical information can be easily supported to upgrade and scale the network.

The Informatics and Information Security Research Center (BİLGEM) of the Scientific and Technological Research Council of Turkey (TÜBİTAK) has developed a new GIS-based active FNMS. The main motivations for the development of such a system, especially for the military market, can be summarized as follows:

- Achievement of detailed management capability for the FON inventory
- Online monitoring of FONs to detect cable aging, breakdown, or intrusion.

Nevertheless, there are five similar commercial systems. These are:

- “ONMS” by JDSU
- “FIBERVISOR” by EXFO
- “RTFS Remote Fiber Test System” by ANRITSU
- “QUESTFIBER” by NETTEST
- “ModBus” and “Unified Monitoring System” by LANCIER

However, there is no other system with the security level supported by the FNMS presented in this study because it has been developed for military FONs. Most other systems have no security services except for the well-known user name/password mechanism. The security level of the developed FNMS is a great advantage for military applications [13].

Nearly all the systems given above include thick-client terminals. They use web-based interfaces as secondary support for some limited operations. Our FNMS, however, provides only one GUI, which is a web-based interface for all operations. Another advantage of the developed system is its increased accuracy and granularity, due to the way of locating the fault coordinates by involving the 3D model of FON cables [14]. Our system can also support more than one test wavelength simultaneously.

2. The developed FNMS architecture

The architecture of the developed FNMS is shown in Figure 1. The FNMS system monitors the FON by actively employing a central server, terminals, and remote test units (RTUs). The central management server (CMS) is composed of hardware and software. The CMS is responsible for the error, performance, security, inventory, and configuration management of the system. All data of the FNMS are stored on the CMS. Client management units (CMUs) are clients allowing authorized access to the CMS. They are used to display queried system data and perform management operations. Terminals access the CMS through a secure web channel.

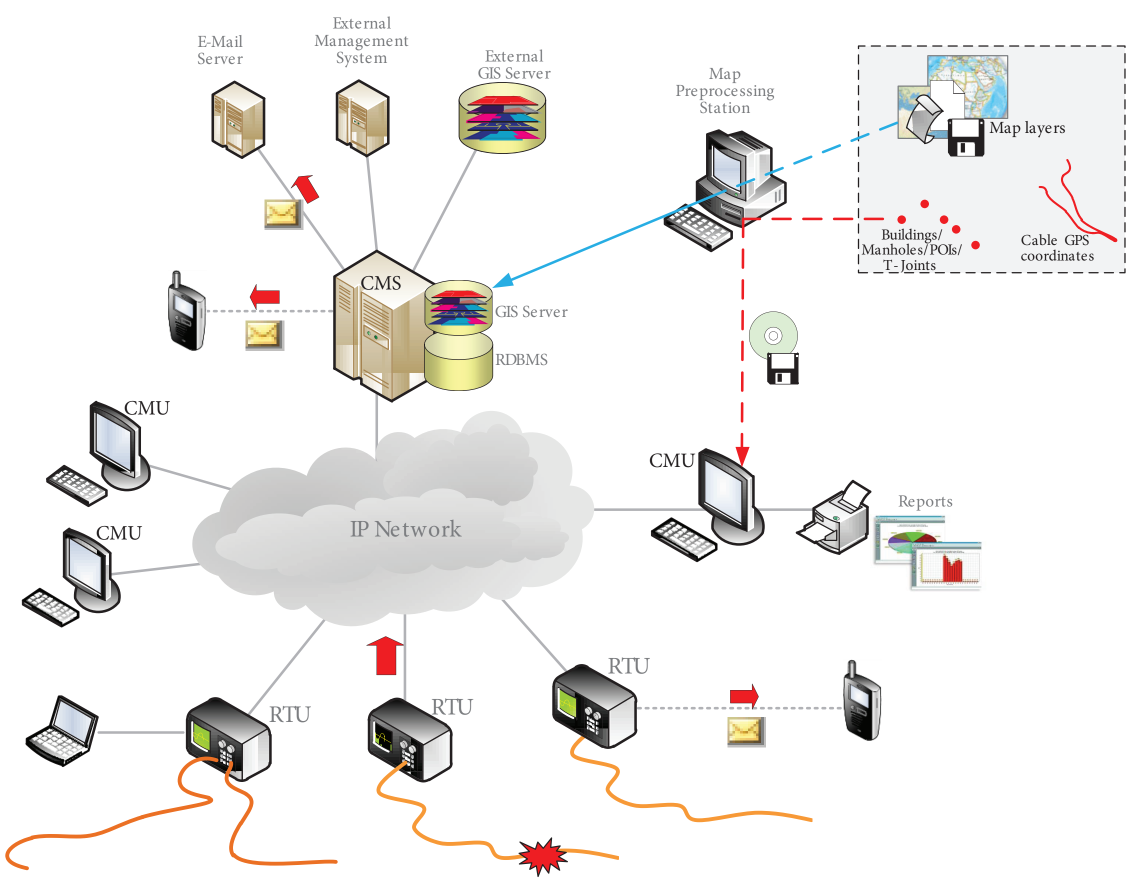


Figure 1. Logical FNMS units.

Detailed information of the concerned FON is sent to the CMUs through the CMS with geographical coordinates and may be updated if necessary. Managing the system, the CMS collects all data, performs all necessary analyses, and serves these data to the users after integration with the GIS data. The CMS also manages the RTUs, which are employed as cable monitoring units. RTU devices are end units located at available nodes in the FON. Their main task is to perform optical measurements on a number of selected fibers and report the measurement results and any alarms (if existing) to the CMS in real time. RTUs perform periodic measurements on FOCs, evaluate the results, and detect cable aging, breakdown, or intrusion and report them to the CMS.

Measurements on the FONs by RTUs can be performed for both dark and active fibers. The results are sent to the CMS periodically under normal circumstances. In case of any alarm condition, they are sent continuously to the CMS. The FNMS includes an RTU designed by TÜBİTAK BİLGEM. The management interface of our RTU is the Web service. However, any other RTU devices in the FON market supporting remote management can be integrated easily with our FNMS.

Operators can manage the FON network inventory and monitor network cables with CMU terminals. By integrating with GIS data, alarm data are displayed on terminal screens. The CMS is located in the central management office (CMO), whereas terminals are located in the regional and subregional management offices. RTU locations are determined by optimization of measurement coverage area and are located at related nodes of the network, as shown in Figure 2.

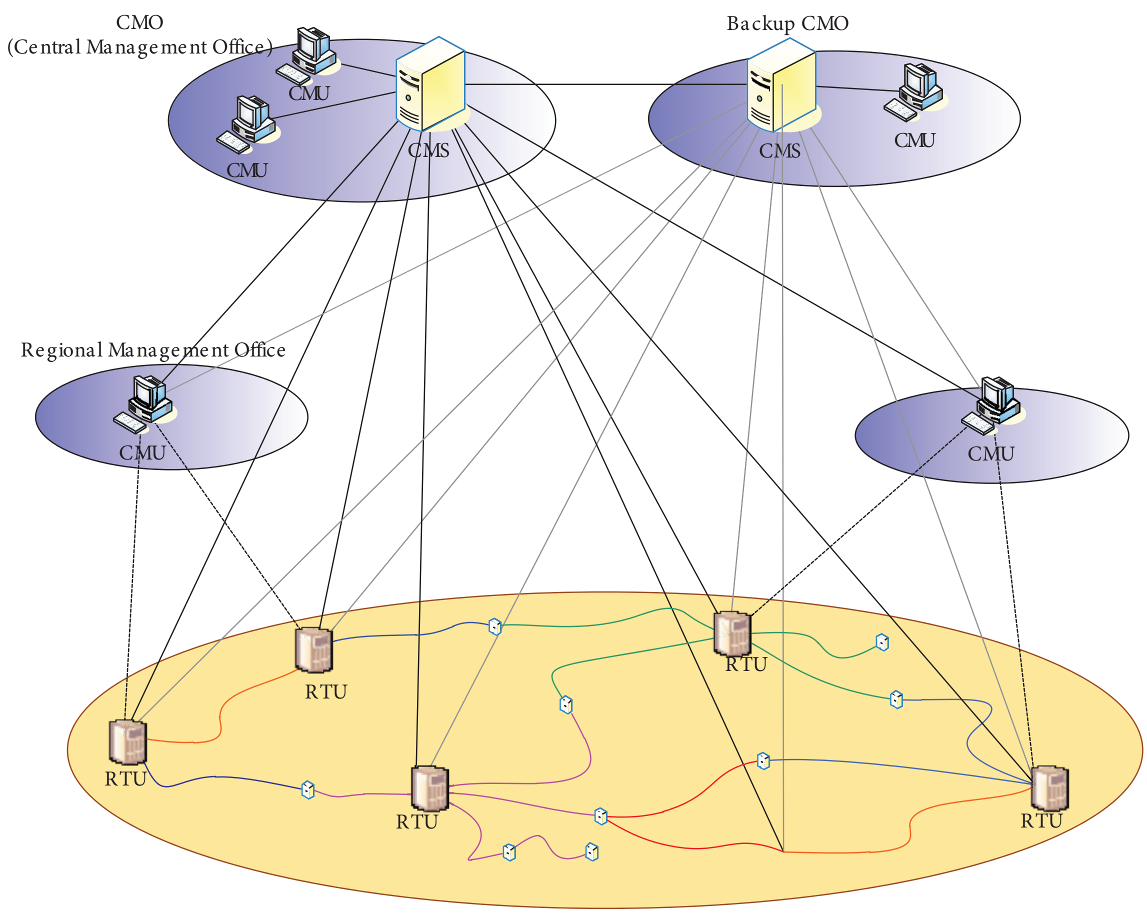


Figure 2. Communications scheme with backup server.

2.1. FON cable monitoring methodology

RTUs can be used to monitor several fibers without any operator interaction by switching the fibers of concern. They can classify types of problems with tested optical fibers and determine the alarm locations as the distance from the beginning of the related cables. The geographical coordinates of the alarm locations are calculated by employing the three-dimensional (3D) geographical coordinate data of the cable network, previously recorded in the CMS database, as shown in Figure 3.

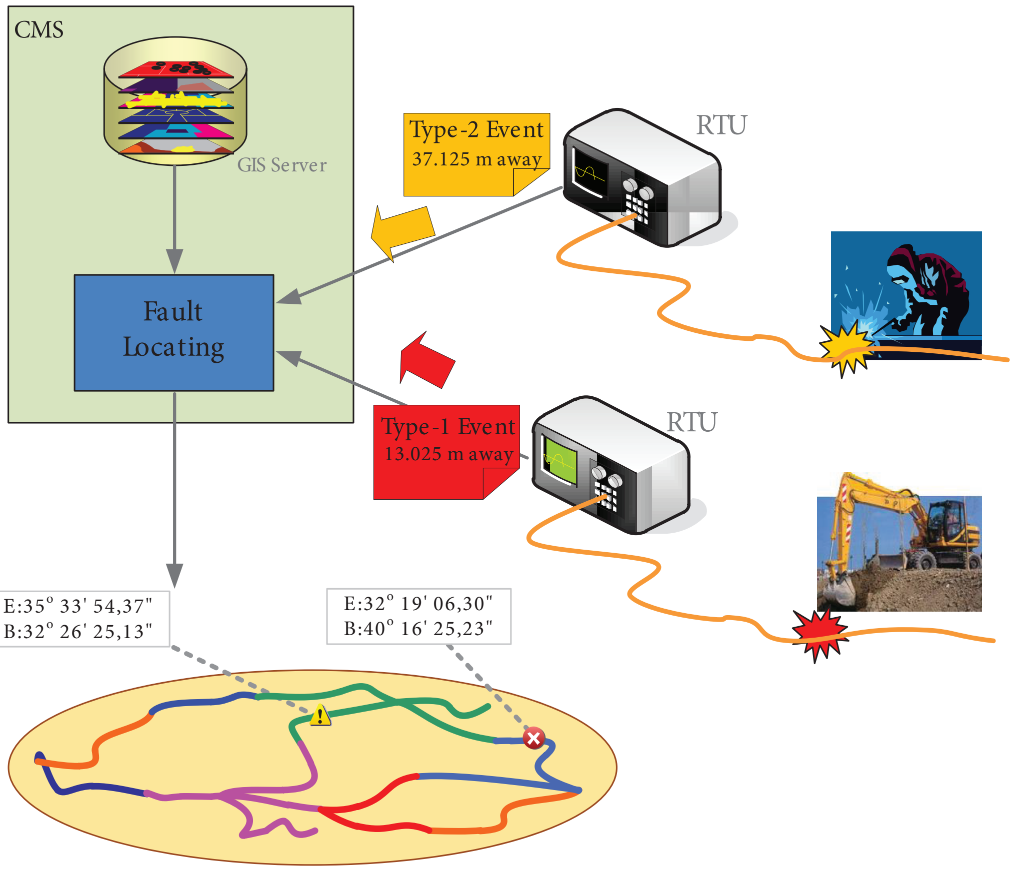


Figure 3. Locating cable faults.

The RTU provides attenuation information by testing the scattering signal. It also provides fault distance by testing the reflection signal resulting from the Rayleigh backscattering principle [15]. The main component behind an RTU is the optical time domain reflectometer (OTDR). The OTDR sends an optical pulse and receives the returning Rayleigh backscattering signal [16,17], which is based on the Fresnel back-reflection principle [18]. After receiving the scattering signal, the OTDR calculates the attenuation of the optical fiber based on the strength of the scattering signal [19].

In optical cables, the reflection may occur on a broken optical fiber, mechanical connection, adapter, or connector [20], due to the different refraction indices on the contact surface of different materials. When an optical pulse signal is sent by the OTDR to be transmitted along the optical fiber, a pulse signal returns to the OTDR due to Fresnel reflection. The distance between the broken point and the connector is calculated based on the time difference between the transmission instant of the optical pulse and the reception instant of the resulting reflection signal. The peaks in the OTDR trace indicate the reflection signals [21]. The pulse power of the back-reflected signal at an instant t is defined as:

$$z = (ct)/(2n),$$

where n is the fiber refractive index. The attenuation of the back-reflected field is proportional to e^{-2az} [22]. The local fiber losses are characterized by converting the temporal evolution of the backscattered signal into a spatial evolution along the fiber. Localized losses present on the link (splices, connectors, breaks, etc.) result in steps with possible reflection peaks in measured trace.

2.1.1. Field installation issues

During the deployment phase of the RTU devices in the field, reference OTDR traces, which represent the normal conditions of the related optical fibers, are determined on the measurement paths connected to their ports.

RTU devices located within the FON are aimed to detect alarm conditions by comparing the results of their periodic measurements to the reference ones. Since there will be deviations from the event metrics belonging to the reference traces of the measurement path due to cable breakdown, aging, intrusion, etc., alarms can be generated as a result of the comparison between the reference and current/real traces. Alarms generated in the case of any difference between the current and the reference traces can be reported to the CMS and to local users with their optical distance and alarm type info (cable breakdown, aging, etc.).

Although RTUs can perform measurements on dark fibers, it is also possible to make measurements on active fibers with traffic by using wavelength division multiplexing (WDM) units integrated into the network. Figure 4 shows a sample scenario of measuring active fiber cables with traffic. Since the cost of an RTU port in a FNMS is quite high, it is crucial to perform measurements on more than one optical fiber at once by considering the maximum fiber length allowed by the limits of the RTU device. Thus, as shown in the figure, bypass connections are employed to connect fibers to each other and to measure more than one optical fiber with the same RTU port.

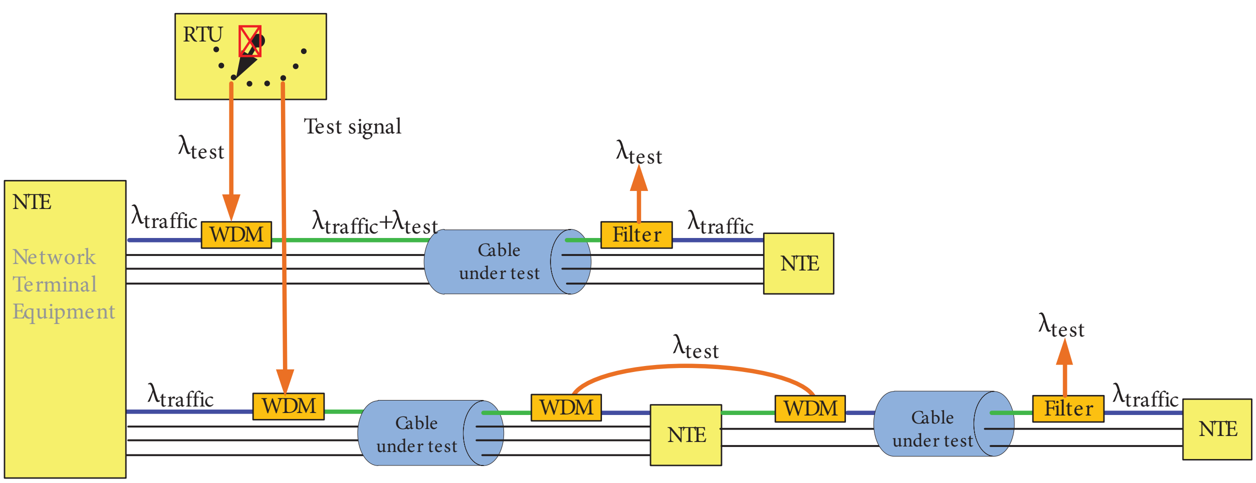


Figure 4. A measurement scenario for monitoring 3 fiber cables.

The CMS is used for the configuration (characteristic parameters of the optical fibers, test parameters, and event and alarm detection thresholds) of the measurement path. Alarm locations detected by RTU on the measurement path are analyzed by the CMS and corresponding cables are determined.

2.2. FNMS modules and technical specs

The system is designed to be operational on a CMS and CMUs that are connected to the transmission control protocol/Internet protocol (TCP/IP)-based network. The FNMS system is operable on a Windows 2003 (or later) server operating system or on Linux. The CMS and the terminals are composed of COTS PC-based hardware and related software.

The GIS server module is deployed on the CMS to store and manage geographical data. Application software modules operate on a Java 2 platform Enterprise Edition (J2EE)-based application server. JavaServer Faces (JSF) pages for the application interface are implemented on Web Container. Data management modules are implemented as Enterprise Java Bean (EJB) and run on EJB Container. Applets [18]embedded in pages are used for handling smart cards, playing the alarm voice, and examining measurement traces.

EJB3 technology, based on Java Persistence Architecture (JPA) defined in J2EE 1.5, is employed. GIS operations are managed by the programming interface of the web application development framework (ADF) [24], provided by the GIS server. For access control, smart cards, including the national smart card operating system (AKİS), are used with PKCS#11 drivers. J2EE technologies are used to decrease dependency on any commercial technologies. JSF is a technology used for the display of GUI components on web pages. It allows applications design with almost all GUI capabilities of a desktop Java application.

Web service is used in the application server for the RTU communications interface. It is necessary to show the effects of certain operations (adding a measurement result, reporting alarms, activating monitoring for a measurement path, establishing a connection to the CMS, and initialization) initiated from the RTU user interface. Java Management Extension (JMX) technology is used for this purpose. This allows existing alarms to be easily reported to external systems such as SNMP trap/notification.

The RTU has 5 main hardware modules. The measurement unit includes an OTDR module for performing measurements on connected optical fibers. The optical switch unit is used to switch the optical signal from the OTDR in order to perform sequential measurements on connected fibers. The communications unit is responsible for communicating with the CMS through the network. The RTU also has a power and alarm unit. Moreover, it provides visual and voice alarm support to its local operators.

3. Basic functionalities and key aspects of the developed FNMS

This section gives detailed information about the capabilities of the system under related titles classified as OSI management services [25].

3.1. Fault management

The definition of measurements to be performed on measurement paths and the management of alarm records with related OTDR traces and actions are covered by a fault management category [26]. There are 2 types of alarm category in the system:

- Device alarms caused by hardware/software failure of CMS and RTUs.
- Fiber alarms caused by breakdown, aging, bending, etc. of FON cables.

Instead of global parameters, it is possible to define the alarm and event detection thresholds for each optical fiber. An alarm message generated by the RTU can involve ample information, such as cable slack data for the measurement path of concern, 3D model info of related optical cables with GIS layer data, geographical coordinates of the alarm location, points of interest (POIs) close to the alarm location, and customer services affected by a related problem.

External e-mail systems can be employed to send notifications to the authorized users in the case of any alarm conditions. The severity of alarm conditions can be modified dynamically for the system. Alarms can either be reported to external management systems compatible with SNMPv1 and SNMPv2 protocols, or they can be announced as voice alarms through CMU terminals. The system also allows handling of detailed records for failure and repair. In addition to the alarms generated by the RTU, other alarms from external transmission systems or cabinets can also be reported to the CMS through alarm inputs of the RTU.

3.2. Inventory management

FON cables are recorded in the FNMS database, being modeled with detailed parameters. Inventory items (FON cables, cable slacks, radio links (RLs), fiber links, manholes/poles, buildings, splice boxes, optical distribution frames (ODFs), and reference points) are stored within the GIS with related location data. Items are modeled as different layers within the GIS subsystem. Cable coordinates are defined as latitude, longitude, and height in 3D space.

Maps within the GIS service help operators to manage inventory data efficiently. The most important advantage of employing layers for mapping is that it allows the optical distances of event locations, measured by RTUs, to be easily transformed into geographical coordinates. Our FNMS is the only system that uses the 3D cable model to determine the event locations precisely. Thanks to 3D support, our system can also provide capability for locating radio link towers by using line of sight analysis.

The system has various facilities that allow its users to specify the 3D model of the FON, as shown in Figure 5. FON information can be fed into the system either by using the drawing tools of the CMU GUI or by supporting GIS-compatible format data from mobile media. For the map processing station of Figure 5, data collected from the field survey are converted into standard GIS format after being preprocessed with a GIS application. Preprocessed data can then be loaded into the system through any CMU terminal. On the other hand, it is also possible to make use of data from external GIS systems in known mapping services format.

FON inventory items are grouped according to the hierarchy of region, subregion, and city. Each subregional commandment office covers a group of cities under its administration.

The system allows the attachment of any type of file to inventory items. Another considerable property of the system is that it allows modification of inventory data with a two-stage confirmation mechanism. Users who are authorized to acknowledge the changes in inventory items are notified by the system with e-mail messages. The first e-mail message is sent only to the primarily authorized user within the subregion where the item is to be modified. After primary approval of this user, another e-mail message is sent to the user holding the right of secondary authorization. These users either accept or dismiss the inventory changes.

3.3. Configuration management

Configuration management category covers the following capabilities:

- Initialization and update of the RTU database (measurement paths, user definitions, security credentials, etc.).
- Remote configuration and state management of the hardware modules (hard disk, OTDR, central processing unit, optical cards, smart cards, etc.) and firmware of RTUs.

- Performing and keeping reference measurements for measurement paths.
- Activating/deactivating monitoring of measurement paths.

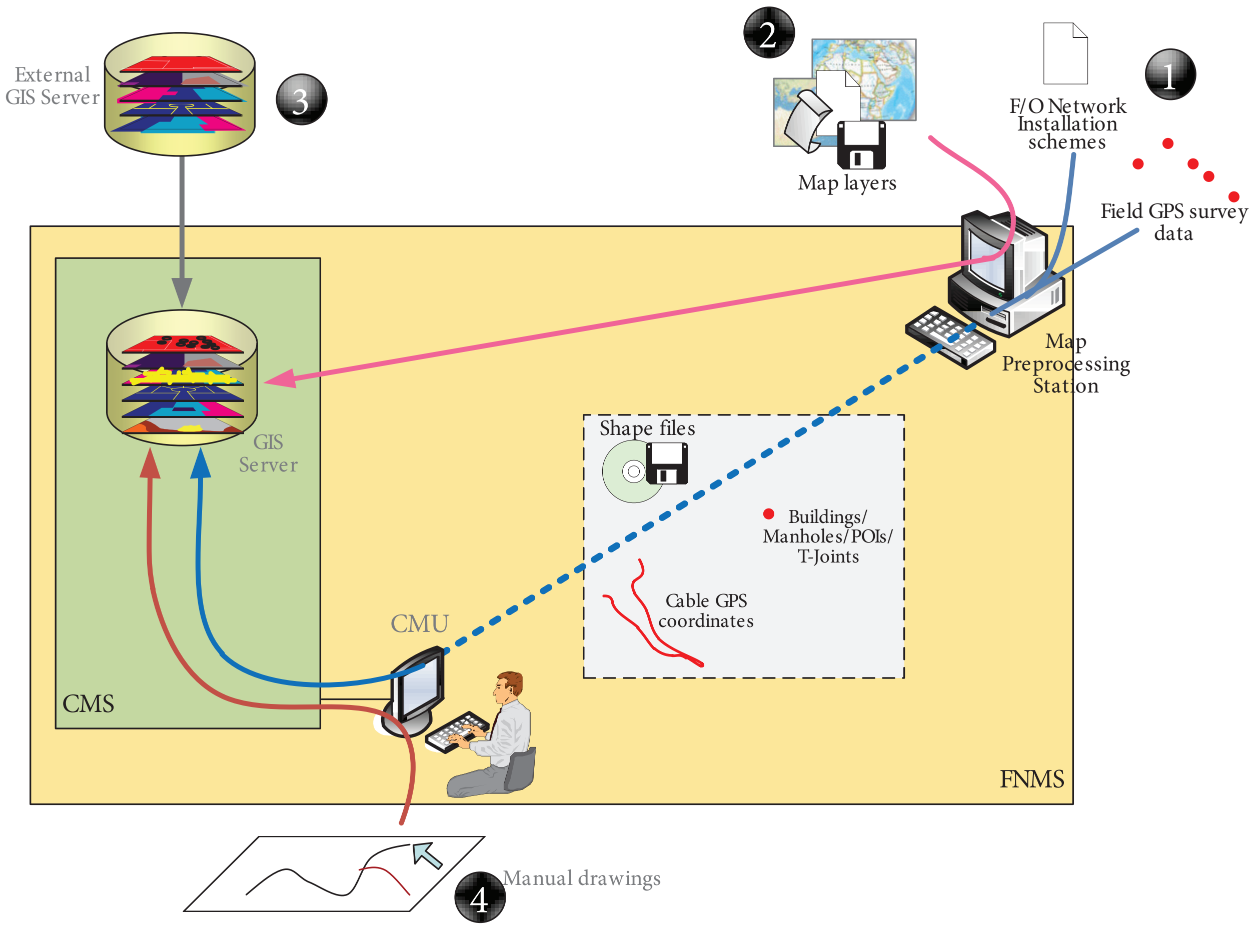


Figure 5. Methodology for geographical data input into FNMS system.

3.4. Security management

The system supports the flexible role-based access control (RBAC) concept. For user authentication, centrally defined user accounts are used. The system enforces smart card and password-based authentication for all operations on FNMS devices, including RTUs. Operator smart cards are issued by the system itself with X509v3 certificates loaded.

There are predefined privileges (allowed operations) that can be assigned to roles and user accounts in the system. There is hierarchy between roles, so that each role can only manage the subroles defined by the users assigned to them.

In addition to the roles and privileges assigned to user accounts, a secondary access control mechanism also exists. The inventory items and FNMS devices can be accessed only by users who are authorized for the subregions in which they reside.

Furthermore, there is an auditing process to keep records of both operations performed by the users and those implied by the system during service. System records represent the history related to system events that occurred in FNMS devices, whereas operation records can be used as the evidence of operations performed by users.

For the security of communications between FNMS devices, transport layer security (TLS)-based mechanisms are employed. To make these security mechanisms work, crypto-parameters should be generated and distributed to all related devices (an operation known as cryptographic initialization). X509 certificates are generated and employed for both users and devices. The system has an embedded public key infrastructure (PKI) for the management of these certificates, where the CMS is the root (and only) certificate authority. TLS certificates to be used for communications between CMS and terminals (supported RTUs) are loaded onto the smart cards.

3.5. Account management

The developed FNMS also has capabilities for management of customer accounts, services (voice, data, video, etc.) provided through the FON network, SLA definitions signed with customers, and SLA realization performance of the FON network.

The link in a fiber circuit is used to construct the FON path, which is composed of a set of optical fibers between 2 buildings. Communications are performed between electronic devices located in buildings at both ends of such a link. The type of communication services provided to customers can be defined for each link. Service downtime and related SLA violations can be calculated for the customer services.

3.6. Performance management

The system has a central database located on the main CMS. The database of the backup CMS, which is reserved to be activated in the case of main CMS failure, is continuously updated with every change in the main CMS database. In the case of main CMS failure, the backup CMS is activated and can establish connections with CMU terminals and RTU devices in a short time.

RTU connection status and user logged-in terminals are monitored. Moreover, automatic and on-demand execution of built-in test (BIT) for RTU are other features for performance management.

3.7. User interface

Web-based user interfaces are used for FNMS terminals. These interfaces are developed using both ICEFaces libraries based on JSF technology and Applet technology.

The operations on user interfaces that are related to each other are grouped with the perspective concept. Web-based interfaces employ mechanisms developed to dispatch GUI updates synchronously to all user terminals. Detailed, flexible, and reusable filters can be defined for all types of information queries and the results of these queries can be exported to files. Symbology filters are used to show entities on the map in different colors with respect to their various properties. All pages have support for context-sensitive help.

The user interfaces of the CMU are designed to support multiple languages by locating all message texts in resource bundle files in universal character set (UCS) transformation format-8 bit (UTF-8) format. The RTU also has a web-based GUI, which can be accessed via local console port or remote network interface.

4. Experimental results

The FNMS system was installed in the field with the following features:

- A CMS and its backup; each has 16 CPU cores and 32 GB of RAM.

- 30 RTUs and 30 CMUs.
- 3D model of 20,000 km of F/O cable network prepared with 25,000 survey points (each has 3D geographical coordinates).
- 20 map layers, including satellite and aerial photos.

The maximum CMS response time for GUI windows including maps is less than 11 s, even in the case of 30 active user sessions from different CMUs. The system provides fair alarm processing performance, in which the transaction for alarm (starting from the notification sent by the RTU and ending with marking the alarm on the map layer) takes 7 s on average.

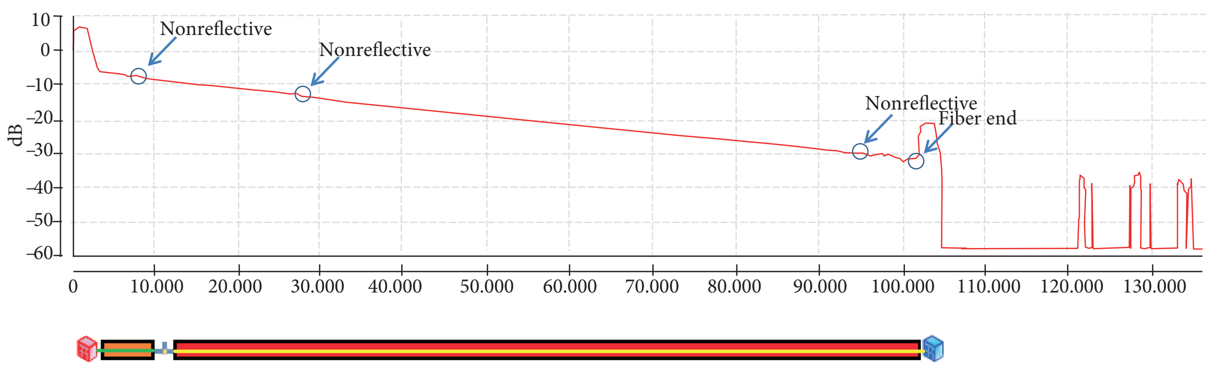
However, because our RTU architecture is based on time-sharing use of a single OTDR module for all measurement paths connected to a single RTU, a longer measurement path means a longer time interval between 2 consequent tests for the same measurement path. Average time for a detailed test of an optical fiber path is approximately 30–40 s.

The FNMS system continuously monitors over 1000 links (optical fiber measurement paths) and reports to the CMS in the case of alarm conditions. The following are trace data with events evaluation obtained from the fielded system. The colored pipes shown under the OTDR traces given in the figures represent the fiber optic cables and the colors of their core claddings and outer sheaths.

- The first example (Figure 6) has the most clear trace data with longer fibers building the link. There are only a few fusion splices with acceptable loss values. This results in a well-used dynamic range with longer measurable distance. In addition, it may be observed that there is no considerable difference between the backscattering coefficient values of the spliced fibers.
- The second example (Figure 7) of trace data includes both reflective and nonreflective events, and the end of the fiber is clearly identified at a distance of about 84,000 m. The nonreflective events of the considered trace correspond to fusion splices. The second and third events indicate gain instead of attenuation, due to different backscattering coefficients for the 2 parts of the splice. The eighth event on the list is reflective due to the existence of a connector. A high reflection value shows a problem with the connector, which is ostensibly due to dirt. The colored line just below the trace data shows the leaves that are spliced or connected to each other to build the link. It may be observed that there is a correlation between the recorded inventory data and the observed trace; however, there are also some differences. This is due to the fact that some fusion splice losses are lower than the event detection threshold values for splices. To prevent such a case, event threshold values should be well determined prior to the measurement.
- The third example (Figure 8) is similar to the second, with both reflective and nonreflective events. However, it may be observed that the end of the fiber is not clearly identified. Additionally, the seventh event shows a reflection that is not followed by an attenuation, which may be due to a ghost.

5. Conclusions and future work

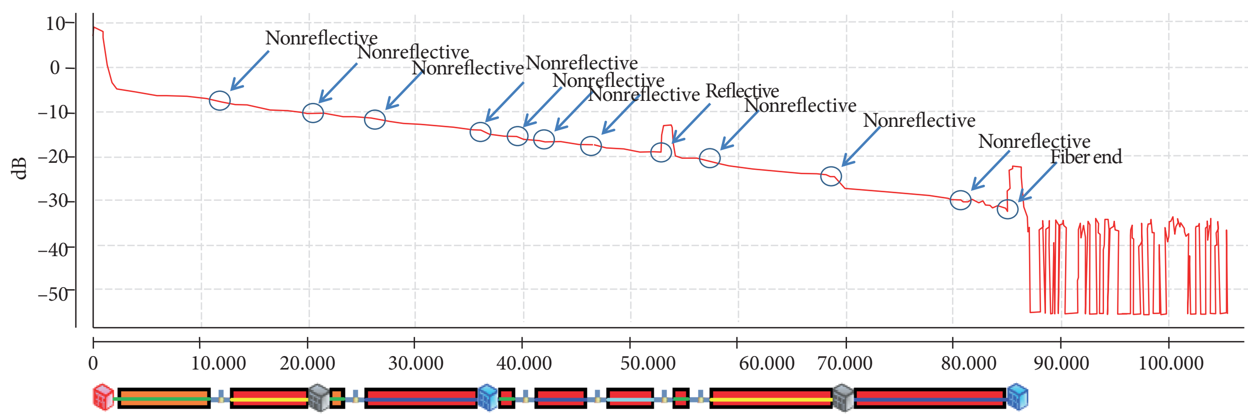
Systems supporting the maintenance of FON networks are gaining higher importance and focus, in parallel with an increase in the employment of fiber optic technology. The COTS systems have higher prices and lack flexibility for any customization. These systems have almost no security mechanisms except for user authentication with a



Events

No	Distance	Reflection	Event Loss	Slope	Total Loss	Event Type
1	8.004.81		0.484	0.266	2.185	Nonreflective
2	27.690.12		0.725	0.242	7.343	Nonreflective
3	94.832.52		1.061	0.242	24.442	Nonreflective
4	101.857.15	–34.97			26.472	Fiber End

Figure 6. Trace example 1.



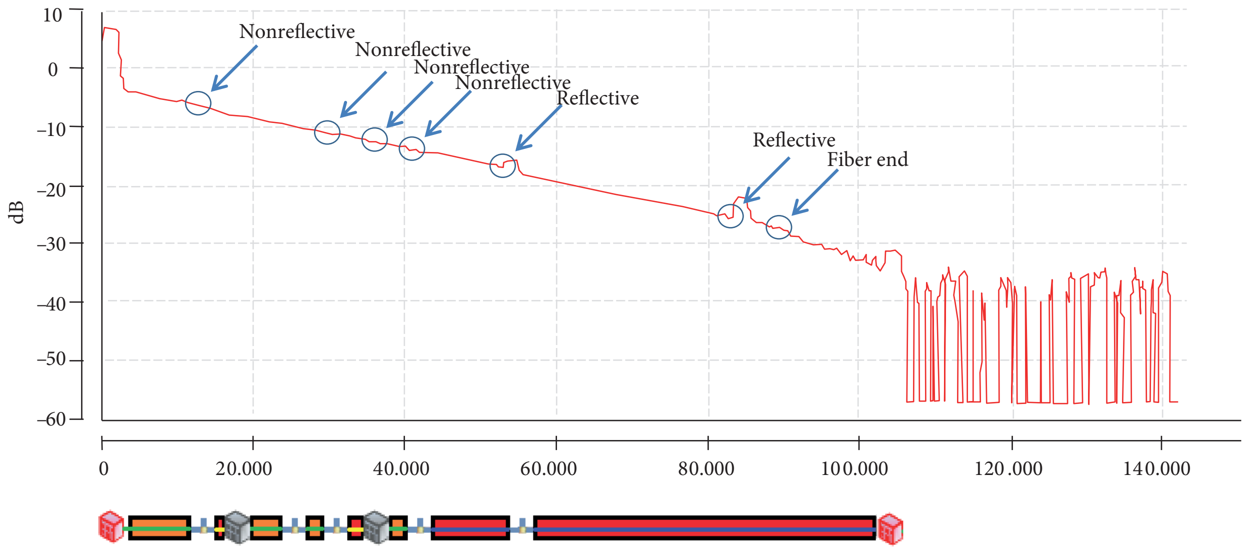
Events

No	Distance	Reflection	Event Loss	Slope	Total Loss	Event Type
1	11.935.75		0.426	0.233	2.876	Nonreflective
2	20.246.87		–0334	0300	5.674	Nonreflective
3	26.291.32		–0.141	0286	7.090	Nonreflective
4	35.899.13		0.566	0.250	9.427	Nonreflective
5	39.339.98		0.197	0.317	11.005	Nonreflective
6	41.892.53		–0.010	0.226	11.807	Nonreflective
7	46.180.82		0.235	0.224	12.741	Nonreflective
8	52.807.26	–28.18	0.644	0.243	14.602	Reflective
9	57.442.70		0.907	0.197	16.212	Nonreflective
10	68.776.04		2.414	0.236	19.754	Nonreflective
11	80.783.26		0.669	0.250	25.204	Nonreflective
12	85.081.76	–20.71			27.721	Fiber End

Figure 7. Trace example 2.

username and password. With the developed FNMS, it is possible to reduce the dependency of the government on foreign systems and target foreign markets instead.

There is ongoing development activity to enhance the capability of optimization in any number of RTU devices to determine their location, in order to cover a FON by considering its topology, number of ports of RTU devices, measurement distance, measurement time, and other operational constraints. A development activity for our own OTDR module has also been initiated. During development, the following issues should be considered for OTDR measurements:



Events

No	Distance	Reflection	Event Loss	Slope	Total Loss	Event Type
1	12.538.15		0.388	0.253	3.154	Nonreflective
2	29.589.22		–0.228	0.249	7.770	Nonreflective
3	35.756.19		0.106	0.258	9.225	Nonreflective
4	40.759.20		–0.073	0.263	10.630	Nonreflective
5	52.827.68	–39.41	0.836	0.253	13.599	Reflective
6	82.988.67	–32.31	–0.259	0.260	22.238	Reflective
7	89.441.52			0.343	24.162	Fiber End

Figure 8. Trace example 3.

- Receiver saturation: the APD receiver can saturate if the OTDR receives high power, resulting in a transient in which the APD does not work properly. In such a case, the resulting measurement is unreliable and the link following the strong reflection cannot be characterized.
- Dead zone: The reflection due to OTDR output connector is often a source of saturating reflections. Measures are unreliable for this type of dead zone. To overcome this problem, a launching span of about 400 m may be used between the instrument and the link.
- Ghost effect: A Fresnel reflection is sometimes observed unexpectedly on an OTDR trace, usually after the end of the fiber. This usually happens when a large reflection occurs in a short fiber. The reflected light bounces back and forth within the fiber, causing one or more false reflections to show up at multiple distances from the initial large (true) reflection. These are called ghost events (reflections).

  Another type of ghosting happens when the range is set as shorter than the actual length of the fiber. This allows the OTDR to send additional pulses of light into the fiber, before the backscatter and reflections from the first pulse have cleared the whole fiber. When there are multiple pulses in the fiber at once, a condition may occur where the returned light from different pulses arrives at the OTDR at the same time, producing “unpredictable results”. Often this will take the form of a series of reflections, or excessive noise, occurring in one area of the fiber.

  The OTDRs we employed are able to analyze the trace and identify the ghosts.
- The end-to-end cable loss is an estimate based on the assumption that the backscatter level of the fiber

link is homogeneous over its length. This is often incorrect due to manufacturing variations or different fibers on each side of a feature. For this reason, end-to-end link loss measurements of the FNMS system need to be analyzed further.

It is also possible to adapt the developed system for planning, modeling, and monitoring of pipelines, railways, power line networks, and transportation networks, where management of GIS-based inventory items is densely employed.

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