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PERFORMANCE ANALYSIS AND APPLICATIONS OF PASSIVE OPTICAL NETWORKS

Özge GÜRE[1], N. Özlem ÜNVERDİ[2]

[1,2]Yildiz Technical University, Electronics and Communication Engineering, İstanbul, Turkey
ozge.gure@superonline.net, unverdi@yildiz.edu.tr

Abstract: *Fiber technology, which provides high bandwidth in data, sound and video traffic in communication networks, as well as in new applications, has reached the end user. FTTH (Fiber-to-the-Home) and PON (Passive Optical Networks) technologies, which reduce costs, have changed our lives. Reaching further distances and more users each passing day is aimed with this structure. In this study, topologies that could be developed to increase the performance of optical communications with passive optical networks are analysed, which is compatible with power budget calculation in theory, with OptiSystem 12.0 simulation program. The effects of electro-optical components which are added to the PON systems are analysed by BER (Bit Error Rate) diagrams, and time domain and spectrum outputs.*
Keywords: *Communication technologies, optical fiber, passive optical networks, bit error rate, fiber to the home.*

1. Introduction

The studies on optical communications which started with John Tyndall's proof that the light can guide the water course in an experiment and Alexander Graham Bell's developing photophone which can transmit sound signals through light, have formed the basis of optical fiber technology which operates according to total internal reflection principle of today. Optical fibers, which have undergone the process of optical cable network ideas for transmitting data, the development of laser and the use of glass fiber as light guide, have now become indispensable data bearers for communication systems. Later on, with various standards applied, a variety of optical fiber types started to be produced following inventions and optical fiber loss was minimized. The types of optical fibers used in communication systems have improved speed, efficiency and appeal to more users and the studies that are carried out for developing better optical fibers have been continuing. Therefore, the use of passive optical networks, known rather as fiber to the home in the world, has transformed optical fiber communications into a new era.

In this study, performance of passive optical networks, which are commonly used today, have been analysed. In the 2nd section of the study, optical communication systems which reach to the end-user are described and the topology of passive optical networks and multiplexing systems are clarified in the 3rd section. Passive optical network applications are analysed by OptiSystem 12.0 simulation program in section 4, and the results obtained are interpreted and reviewed in section 5.

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2. Fiber Systems To The End User

The general term for fiber networks that reach to the end-user are referred to as "FTTx" and the term "x" stands for the differences in applications. Different "x" terms can be explained as such:

In FTTB (Fiber to the Building), the optical fiber which comes off the switching device in the central switchboard office reaches to the boundary of the building and the flats in the building are then served through the twisted-pair cable. In FTTC (Fiber to the Curb), the optical fiber which comes off the switching device in the central switchboard office is carried to a switching device which is within 300 m. of the subscriber. From this point, coaxial cable, twisted-pair copper cable or optical fiber are used to serve the customer according to the subscriber's preference. In FTTH (Fiber to the Home), the optical fiber which comes off the central switchboard office equipment is carried directly to the home user. In FTTCab (Fiber to the Cabinet), the optical fiber is furnished within a distance of about 1 km. to the subscriber and this application is called FTTN (Fiber to the Node) [1].

3. Passive Optical Networks

As seen in Figure 1, PON is composed of OLT (Optical Line Termination), ONU (Optical Network Unit), the optical splitter which splits and combines the flow of information between OLT and ONUs and the optical fiber cables that connect these devices.

The OLT unit which is placed in the central office ensures the dual transmission of data through optical distribution network. The OLT device distributes the voice, data and video traffic imported from the local network for downstream transmission. In upstream transmission, in contrast to downstream transmission, the device is responsible for importing data of various content and types and distributing it locally.

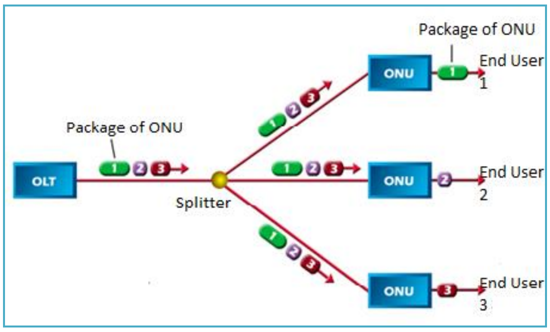

Figure 1. Passive optical network components.

The ONU is placed directly in the home or the office of the user. This device, also called ONT, ensures the required electrical-optical transformations and forms a connection point within the optical network [2, 3].

The optical information that comes off the OLT is distributed to all ONUs with the demultiplexer and ONUs run the information received if it is sent to it. It is important to ensure the confidentiality of the packages sent by the services to be developed since ONUs also receive the information that does not belong to it. As only one optical fiber line will have to be used from all ONUs to OLT, multiple access systems such as TDMA (Time Division Multiple Access) and WDMA (Wavelength Division Multiple Access), which prevent the collision of data sent on the line, have to be used.

ODN (Optical Distribution Network), generally points out to the components which ensure the transmission between OLT and ONT and the transmission environment. Topologies such as road topology, circuit topology, star topology, tree topology and mesh topology are used in passive optical networks formed by a splitter, optical fiber cables, attachment cabinet and site cabinet by taking the locations of subscribers, physical features, environmental conditions and cost into consideration.

Passive optical networks are classified as APON (ATM PON), BPON (BroadBand PON), EPON (Ethernet PON), GPON (Gigabit PON), GePON (Gigabit Ethernet PON) and NGPON (Next Generation PON) in terms of the technology, speed and the multiplexing method they support [4].

In APON technology, the connection between OLT and ONU is built as connection-oriented virtual circuits ATM (Asynchronous Transfer Mode). G.983.1 includes the APON architecture with symmetric 155 Mbps upstream and downstream bit speed. This feature was improved in 2001 and BPON appeared with 155 Mbps upstream and 622 Mbps downstream and symmetric 622 Mbps transmission.

In EPON technology, in contrast with other PON standards, the ethernet standard is basically used. Instead of stable ATM cells, ethernet packages whose length can change are used for data transmission. The ethernet technology ensures easy management, connection on the basis of ethernet, and the operation of customer and central IP (Internet Protocol) equipment.

GPON technology, which is broadcast with G.984 standard, is an improved version of BPON technology. It is generally used with 2488/1244 Mbps upstream/downstream speed although it supports high speeds such as 2488 Mbps symmetrically. Instead of old generation ATM frames in BPON, the use of the frame called GEM (GPON Encapsulation Method) has one of the advantages of GPON architecture which supports the optical split ratio to 128. With this topology, framing of different packages such as TDM, Ethernet and IP is ensured [5]. GPON technology is the most commonly used passive optical network type.

4. Applications of Passive Optical Networks

4.1. Changing the Features of Components of Passive Optical Networks

In communication systems, there are many methods to determine the receiver sensitivity of the system and the quality of the service. One of these methods is BER (Bit Error Rate) calculations.

BER is frequently used to express the bit rate which is distorted or received wrongly in the data sent during information transmission and in fiber systems calculations [6].

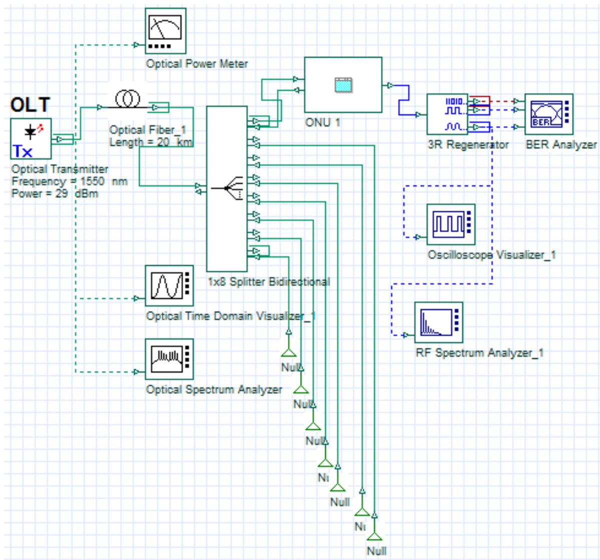

Figure 2. Sample reference passive optical network topology.

The reference topology, which is designed with 1550 nm downstream 20 km single-mode optical fiber and 1/8 splitter is shown in Figure 2. When the length of optical fiber on the reference topology is analyzed, the eye patterns which were obtained from the reference topology and the topology which was conducted with 50 km optical fiber are given in Figure 3. In the 20 km system, all the data to be transmitted reached the ONUs; in other words, the BER value was calculated as 0 and the maximum quality factor value was 97.95. The system losses increased, the vulnerability of the eye pattern increased and the pattern became unstable which led the quality factor to fall to 17.18 with the insertion of 30 km optical fiber to the system which had a 29 dBm transmitter power. The decrease in the height of the eye pattern and the increase of jitter are the indicators of decrease of efficiency because of the increasing system losses.

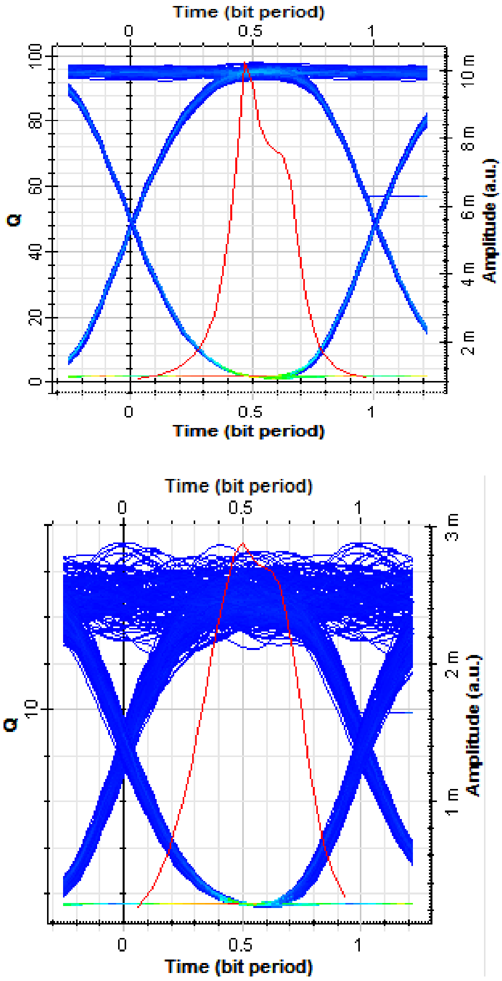

Figure 3. Eye patterns in 20 km. and 50 km. optical fiber networks.

In the reference topology, when the type of the optical fiber was changed and a 20 km multi-mode optical fiber was used, the quality factor was 0 and there was no data transmission in the system. If a multi-mode optical fiber was used in the system, transmission was observed only if the fiber length was less than 10.5 km. If the data communication quality in the single-mode optical fiber is demanded in multi-mode optical fibers too, the length of the optical fiber which must be used is less than 1 km. Therefore, the multi-mode optical fibers are not preferred in long distance communications. The excess loss mentioned results from the differential group delay ($\Delta\tau_g$). The equation below is obtained by

$$\Delta\tau = \frac{L}{\Delta v_g} = \frac{d\Delta B}{dw} L = \left(\frac{\Delta n}{c} + \frac{w}{c}\frac{d\Delta n}{dw}\right) L \qquad (1)$$

taking the derivative of propagation constants with respect to the frequency. Here, Δv_g signifies the difference between group speeds of orthogonal modes, w stands for the angular frequency of the light, c shows the velocity of light in space and $\Delta n = n_s - n_f > 0$ indicates the refractive index difference between the fast and slow axes. While the value of $\Delta\tau/L$ is expressed in ps/km in a short fiber part, it is proportional to the square root of fiber length in long fibers [7].

In the reference topology, the changes in the features of the optical fiber led to significant distortions in the system or increase of quality. For instance, in the topology where a 20-km. single-mode optical fiber was used, when the dispersion in the current optical fiber was 16.75 ps/nm/km, data transmission was provided and the quality factor was around 97.95, on the other hand, when the dispersion was 50 ps/nm/km, the quality factor was 37.41 and when the dispersion was 75 ps/nm/km, the quality factor was 31.18. Despite the fact that changing dispersion values affected the quality factor of the system, dispersion and quality factor are not exactly inversely proportional to each other.

One of the main elements that affect the quality of data transmission in passive optical communications is the splitter. The changes in this element directly affect the system. A change of state was reviewed in line with some characteristic features of the splitter in the topology of 20 km line realized with 8 separations through a 29 dB WDM transmitter. It was observed that the power transmitted from OLT to one of the ONTs was 11.790 dBm when the insertion loss was 1.5 dB, the return loss was 65 dB and the noise dynamic was 3 dB in the splitter. When the insertion loss was 10 dB, it was seen that the power transmitted to ONT was 3.290 dBm. This case showed that attenuation had an impact on the power transmitted to each ONT. When the insertion loss was 6 dB, a 7.290 dBm power was transmitted to the single ONT and the loss of 4 dBm directly affected the subscriber. At this point, it is clearly seen that the insertion loss plays a critical role in passive optical networks. The effect of the return loss was also observed in practice. When the return loss was 65 dB, a 11.970 dBm power was transmitted to ONT. When this loss became 100 dB, a 7.290 dBm power was transmitted to ONT and there was a 4 dB loss. When the return loss was decreased to 10 dB, the power transmitted to ONTs was 7.296 dBm. This case shows that when there are major changes in the network, the return loss is as effective as the insertion loss. The increase of noise dynamic in the splitter will directly affect the topology. In a 3 dB noise, the power transmitted to each of the ONTs was 11.970 dBm; whereas in a 6 dB splitter noise, there was a 7.290 dBm power transmission. The split ratio is one of the most important factors through which the splitter affects the system in passive optical network topologies.

Today, the split ratio of up to 128 is supported in GPON topologies in theory; however, this ratio is lower in practice due to the fact that the increase of separation number in industrial applications increases the splitter losses which influences the system. The change in the quality of the signal received with separation of 4 instead of separation of 8 was analyzed in the topology with 20 km single-mode optical fiber. In a sample BPON formed by bidirectional optical fiber, the quality factor obtained from each ONT was respectively 9.4, 18.85 and 37.53 in cases with split ratios of 8, 4 and 2 in the system.

4.2. Insertion of Electro-Optical Components into Passive Optical Network Topologies

The subscriber line in passive optical networks or the values required for the calculations for optical fiber networks vary depending on the intended use. For that reason, different electro-optical components may be inserted into the system. In this section, the effects of electro-optical components on the system are reviewed. In a PON architecture designed with a splitter of 8 separations and 0 dBm in a 20 km line realized with single-mode fiber, the quality factor obtained from a ONU is 18.93 and the minimum BER value is $2.7x10^{-80}$. When a Mach-Zehnder modulator was inserted to the PON topology, the results obtained were reviewed and it was seen that the Mach-Zehnder modulator decreased the quality factor of the system to 11.5. Optical modulators affect the system by changing the refractive index as a function of the external electric field applied.

In the passive optical networks, another component which is used more frequently is the optical amplifier. Many optical amplifiers strengthen the light through stimulated emission. The mechanism is similar to lasers in that sense. In fact, the optical amplifier is a laser without feedback. The optical gain, which is the main parameter, is ensured with the pumping of the amplifier for realizing the population inversion. The optical gain depends not only on the frequency of the signal received, but also on the local beam density in any point in the amplifier. EDFA (Erbium Doped Fiber Amplifier), Raman amplifier, semiconductor optical amplifier and waveguide amplifier are examples of optical amplifiers. EDFA was found to be the most efficient for the topologies in this study in terms of gain.

The optical time domain indicator and the frequency domain graphics obtained from the optical spectrum analyser of the basic system which has 16 separations in 20 km distance and the system with EDFA were compared at only one ONU exit in Figures 4 and 5.

When a 5 m long EDFA was inserted into this topology, the noise amplitude decreased and the spectrum power rose to -0.1 dBm ($974.78x10^{-6}$) from -20 dBm ($9.6x10^{-6}$) according to the waveforms at the exit of ONU. Besides, in the first topology, while the max Q factor was 9.5 and the eye height was $8.3x10^{-22}$ obtained from the BER diagram, the max Q factor was 500.9 and the eye height was 0.0015 with EDFA insertion.

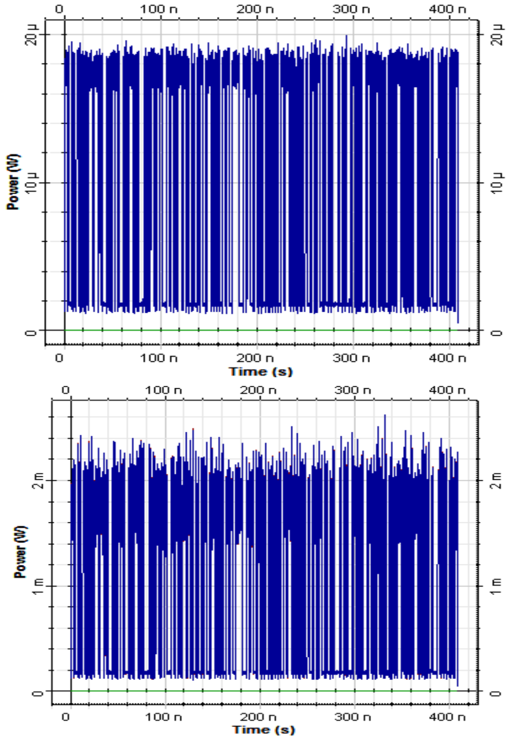

Figure 4. Power graphics in reference topology and topology with EDFA insertion.

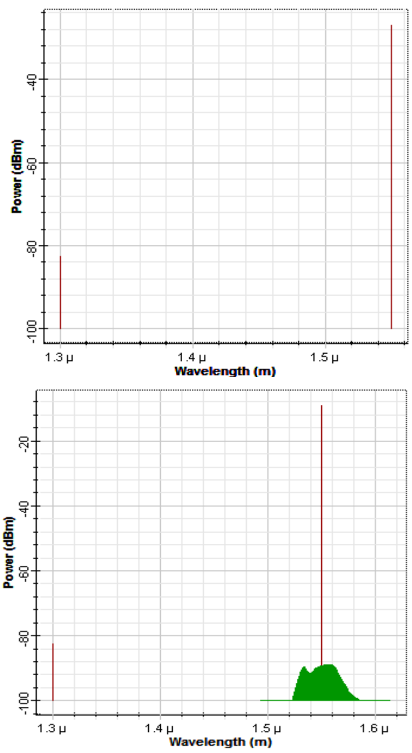

Figure 5. Spectrum graphics in reference topology and topology with EDFA insertion.

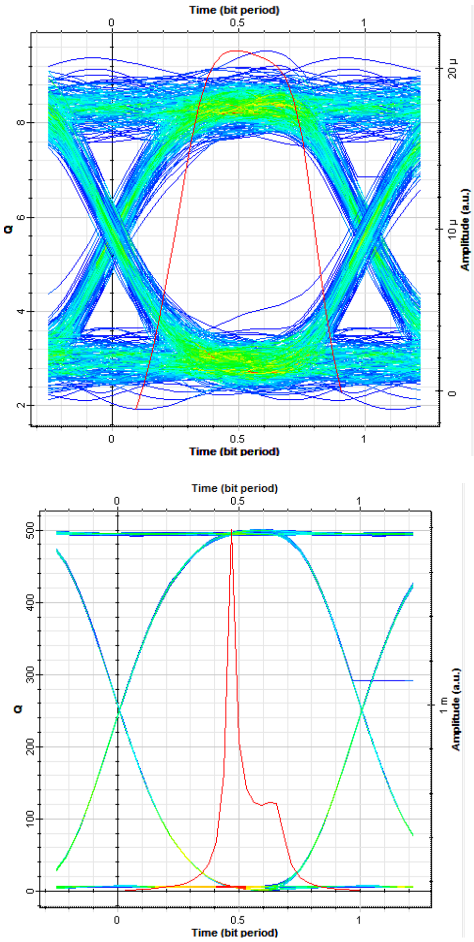

Figure 6. BER graphics in referential topology and topology with EDFA insertion.

One of the electro-optical couplers which can be used in passive optical networks is the optical fiber couplers. An optical directional coupler has two parallel, two twisted or one straight and one twisted optical fiber. Since the distance between the axes of optical fibers is very close as opposed to the operation wavelength, evanescent areas interact reciprocally. Mutual coupling between the optical fibers is analyzed through Coupled Mode Theory and Perturbation Theory [8]. A sample topology where optical directional coupler designed with OptiSystem 12.0 simulation program added to the passive optical network can be seen in Figure 7.

Optical filter insertion may be needed in a passive optical network topology. Optical filters are based on the principle of absorption and reflection of light in a certain wavelength. Large or small components of the frequency spectrum are used and filters have some effects on the PON topology depending on the width of the spectrum used. In this way, a process can be realized in the desired frequency interval. In practice, in the passive optical network operated on the level of THzs, a rectangular filter with a 10 GHz bandwidth was inserted after the WDM transmitter and only 1.55248 μm and 1.55256 μm wavelength interval was effective in the system and this case decreased the general efficiency of the system, but it had an impact on the desired frequency range.

Today, the splitting task is carried out with splitters in passive networks around sites furnished with optical fiber cables. Coupler is, on the other hand, used when a large amount of the sign is employed for usual communication and a small amount is left for calculations.

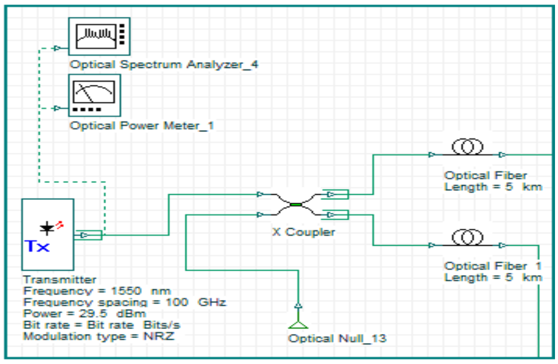

Figure 7. PON topology with directional coupler.

In a simulation environment, the coupling coefficient value is changed and the specified goal is achieved. For instance, in Figure 7, in the topology where the transmitting part, coupler and optical fiber part is shown, when most of the signal is required to pass through the upper arm, the coupling coefficient is made 0.1 with a 90% and 10% separation ratio and the transmitted power values are reviewed again. The power value on the upper arm exit of the coupler was calculated as 26.432 dBm, i.e. 439.76×10^{-3} W and the power value on the lower arm exit was calculated as 16.890 dBm, i.e. 48.862×10^{-3} W. The power transmitted by the upper arm is 9 times the power transmitted by the lower arm and a ratio of 90% to 10% was obtained. In that case, while the power transmitted to ONT was 61.824×10^{-3} W for the upper arm, it was determined as 6.869×10^{-3} W for the ONT after the splitter was supported by the lower arm. All the data was transmitted successfully through both arms and the desired power transmission ratio was ensured.

5. Conclusion

In this study, passive optical networks, which are significant in today's communication technologies, were analyzed and the performance of circuit elements used in some topologies designed with OptiSystem 12.0 simulation program were reviewed. The effects of the type, length and dispersion values of the optical fiber used in the network and the additional loss, return loss and the noise dynamic parameters of splitter, which is one of the main components of passive optical networks, on the system were analyzed. By adding an optical modulator, optical amplifier, optical filter and an optical coupler to the passive optical network, the factors which can affect the efficiency of the passive network topology positively or negatively were reviewed through BER diagrams, time domain and spectrum outputs. As a result of the measurements carried out, an increase in efficiency on the second window in 1300-1350 nm and on the third window in 1500-1550 nm in passive optical networks was observed.

6. Acknowledgement

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O. Gure was born in 1987 in Kirklareli, Turkey. She received her B.S degree in Electronics and Communication Engineering from Electrics & Electronics Engineering Department of Yildiz Technical University, Istanbul, Turkey in 2009. She graduated from Yildiz Technical University with a Masters degree from the same department, in 2012. Since 2009 she has been working as a Project Engineer in Superonline which is a service provider in Turkey. Beside network applications, she is interested in optical devices and optical communication systems.

N. O. Unverdi was born in 1967 in Aydin, Turkey. She received her B.S degree in Electronics and Communications Engineering from Electrics & Electronics Engineering Department of Yildiz Technical University, Istanbul, Turkey, in 1989. She earned her M.S and Ph.D degrees in the field of Communications from the same university in 1991 and 1998, respectively.
She has worked as a Research Assistant at Yildiz Technical University, Electrics & Electronics Engineering Department, Electronics and Communications Engineering Division, Istanbul, Turkey between 1990 and 1999. She has been working as an Assistant Professor in the same department since 1999. Her research areas of interest include optical communications, optical waveguides, communications systems, transmission technologies, antennas, propagation and bioelectromagnetism.