Transmission Characteristics of Radio over Fiber (ROF) Millimeter Wave Systems in Local Area Optical Communication Networks

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ABSTRACT

In the present paper, we have proposed Radio over fiber (ROF) technology which allows radio frequency (RF) transmission directly over the optical fiber has attracted much attention due to its promising performance and operational cost reduction. The well known advantages of optical fiber as a transmission medium such as low loss, light weight, large bandwidth characteristics, small size and low cable cost make it the ideal and most flexible solution for efficiently transporting radio signals. We have presented and modeled with parametrical investigation the transmission performance characteristics of the ROF system that is modulated with multiple bit rates using different transmission techniques such as Soliton, and maximum time division multiplexing (MTDM) technique. These transmission techniques are employed through two ultra multiplexing techniques, 4 links space division multiplexing (SDM) plus multi channels dense wavelength division multiplexing (DWDM) over optical window of special interest. Moreover, we have analyzed and investigated Soliton, and MTDM transmission techniques to be processed to handle both transmission bit rate and product either per link or per channel for cables of multi-links (4-24 links/core).

Keywords- Fiber radio networks, Wavelength division multiplexing (DWDM), Space division multiplexing (SDM), Radio over fiber (ROF), Hybrid fiber radio systems.

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I. INTRODUCTION

The demand for broadband services has driven research on millimetre (mm) wave frequency band communications for wireless access network due to its spectrum availability, and compact size of radio frequency devices [1]. However, the mm wave signals suffer from severe loss along the transmission as well as atmospheric attenuation. In other words, upcoming wireless networks will use a combination of air interface methods in different channels and in different cells that can be changed dynamically to meet variations in traffic conditions. One of the solution to overcome these problem is by using low attenuation, electromagnetic interference-free optical fiber. Radio over Fiber (ROF) is integration of optical fiber for radio signal transmission within network infrastructures that is considered to be cost effective, practical and relatively flexible system configuration for long-haul transport of millimeter frequency band wireless signals. Fiber optic LANs will be carrying traffic at data rates of tens of gigabits per second in the near future, whereas data rates of tens of megabits per second are difficult to provide to mobile users [2]. In this regime, optical channels, offering terahertz of bandwidth [3], have many advantages. First ROF systems were mainly used to transport microwave signals, and to achieve mobility functions in the central office or exchange (CO). That is, modulated microwave signals had to be available at the input end of the ROF system, which subsequently transported them over a distance to the RS (Remote Site) in the form of optical Today ROF systems, are designed to perform added radio system functionalities besides transportation and mobility functions. These functions include data modulation, signal processing, and frequency conversion [4]. For a multifunctional ROF system, the required radio signal at the input of the ROF system depends on the ROF technology and the functionality desired. ROF offers operational benefits in terms of operational flexibility. Depending on the microwave generation technique, a ROF distribution system can be made signal format transparent. The Intensity Modulation and Direct Detection technique can be made to operate as a linear system and therefore as a transparent system. A fiber radio network is a hybrid network that uses an optical network to deliver wireless data from a CO to remote radio Base Stations (BSs). The CO provides the interface between an external network. A fiber-radio network differs from a traditional fiber-to-the-home (FTTH) access network in that the transported data is at a wireless frequency and not at baseband [5]. One promising alternative to the first issue is an ROF based network since in this network functionally simple and cost effective BSs are utilized in contrast to conventional wireless systems. However, the second issue is still challenging and difficult to realize as the conventional handover procedures cannot easily be applied to the system. In first ROF network architecture operating at mm-wave bands with special emphasis on mobility management. Specially, our concern is how to support fast and simple handover in such networks using ROF network's centralized control capability. In addition, an ROF based broadband wireless access network architecture is proposed, where wavelength division multiplexing (WDM) is utilized for bandwidth allocation.

A fiber-radio network comprises two distinct domains, one optical and one wireless. In the optical domain, Wavelength Division multiplexing (WDM) can be use to combine several wavelengths together to send them through a fiber-optic network, greatly increasing the use of the available fiber bandwidth and maximizing total data throughput that in order to meet future wireless bandwidth requirements, a single CO feeds each remote radio BS and has access to a separate optical WDM involves multiplexing multiple wavelengths and transporting them in a single fiber. Current technology allows one to two hundred channels to be transported in a
single fiber, achieving Tb/s total capacity If WDM is used
in a fiber-radio network, then each BS can be assigned a single wavelength. A WDM network requires wavelength selective optical components that can multiplex or demultiplex channels or that can drop or add channels These components are imperfect and can not fully remove unwanted channels, leading to optical crosstalk, i.e. the presence of an undesired optical signal .Although optical components can reject adjacent wavelength channels by up to 30 dB [6] or more some residual signals will still be present, particularly if channels powers are unequal. This type of unwanted crosstalk is referred to as inhomodyne or heterodyne or inter- channel crosstalk, or simply as out-of band crosstalk. This type of crosstalk does not severely impair network performance as it is at a different wavelength as the desired signal and is simply added to the signal in the electrical domain [7].

In the present study, we have investigated the propagation problems in ROF systems, in addition to its transmission properties, the insensitivity of the fiber optic cables to electromagnetic radiation is a key benefit in their implementation as the backbone of the advanced optical communication networks. Moreover, we have presented the transmission capacity of ROF systems with different transmission and multiplexing techniques to be processed to handle bit rates either per link or per channel for cables of multi links in the fiber cable core. Where maximum number of transmitted channels are processed to handle the product of bit rate either per channel or per link for cables of multi-links.

II. BASIC ROF ARCHITECTURE

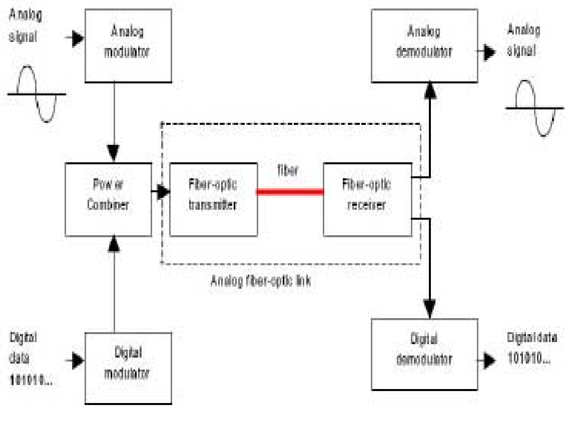

Fig. 1. Basic Radio over Fiber (ROF) structure.

Figure 1 shows a typical radio frequency (RF) signal (modulated by analog or digital modulation techniques) being transported by an analog fiber optic link. The RF signal may be base band data, modulated intermediate frequency (IF), or the actual modulated RF signal to be distributed. The RF signal is used to modulate the optical source in transmitter. The resulting optical signal is launched into an optical fiber. At the other end of the fiber, an optical receiver that converts the optical signal to RF again. By delivering the radio signals directly, the optical fiber link avoids the necessity to generate high frequency radio carriers at the antenna site [6]. Since antenna sites are usually remote from easy access, there is a lot to gain from such an arrangement. Usually a single fiber can carry information in one direction only (simplex) which means that we usually require two fibers for bidirectional (duplex) communication. However, recent progress in wavelength division multiplexing makes it possible to use the same fiber for duplex communication using different wavelengths. DWDM can be use to combine several wavelengths together to send them through a fiber optic network, greatly increasing the use of the available fiber bandwidth and maximizing total data in order to meet future wireless bandwidth requirements [7].

III. MODELING ANALYSIS

The performance of ROF systems, as well as in traditional optical communications networks, can be affected by linear and nonlinear impairments. Particularly, in ROF systems, the fiber chromatic dispersion can degrade the transmitted Radio Frequency (RF) signal by means of fading effects. The fading effect can lead to cosine like fluctuation of the signal power along the fiber, which means that the signals periodically vanishes at specific pairs of frequencies and fiber lengths. This phenomenon is similar to multipath effect in wireless systems and happens because sidebands around the optical carrier, arising from modulation process, travel into the optical fiber with different group velocities [8].

A) ROF DISPERSION MODEL

The performance of radio over fiber systems can be affected by linear and nonlinear impairments. Particularly, in ROF systems, the fiber chromatic dispersion can degrade the transmitted RF signal by means of fading effects. First order dispersion changes phase of each sideband relative to the carrier [9] as:

$$\varphi = \frac{1000\pi L_f \, D_t(\lambda)\lambda_c^2 \, f_{RF}^2}{c}, \qquad (1)$$

Where L_f is the fiber link length, φ is first order dispersion, λ_c is the central wavelength, f_{RF} is the RF frequency, c is the light speed (is equal to 3×10^8 m/sec) and D_t is the total dispersion coefficient as a function of operating wavelength in the fiber media is given by the following expression as the following [10].

$$D_t(\lambda) = -\frac{\lambda_s}{c}\frac{dn}{d\lambda} - \frac{\Delta\lambda}{2c}\left(\frac{d^2n}{d\lambda^2}\right) - n_2\left(\frac{\Delta n}{c\lambda_s}\right)F(V), \qquad (2)$$

Where n_2 is the refractive-index of the cladding material, Δn is the relative refractive-index difference, λ_s is the operating signal wavelength, F (V) is a function of V number (normalized frequency). Based on the work [10], they designed the function F (V), with employing V number in the range of ($0 \le V \le 1.15$) yields:

$$F(V) = 1.38V - 6.98V^2 + 13.45V^3 - 4.84V^4 - 1.48V^5, \qquad (3)$$

In our simulation model design, we are taking into account V-number as unity to emphasis single mode operation [10]. Based on Ref. [11], the refractive index of pure silica waveguide as optical fiber media is cast under the Sellemier equation. The parameters is adjusted as:

A= 0.691663, B= $(0.068404)^2$ $(T/T_0)^2$, C= 0.407942, D=$(0.1162414)^2$ $(T/T_0)^2$, E=0.8974749, and F= $(9.896161)^2$. Where T is ambient temperature in K, T_0 is the room temperature and is considered 300 K. Then the first and second differentiation of Sellemier equation with respect to operating wavelength λ as in the series of equations in [4].

B) ROF ATTENUATION MODEL

Almost all ROF links use single mode fiber. Hence the fiber dispersion is not an issue with ROF links up to several tens of kilometers when the RF frequencies are less than 10 GHz. Fiber attenuation is a function of wavelength. Modern fibers offer as low as 0.2 dB/km loss at 1.55 µm. Connectors and splices will add few more dB loss. The optical losses together can be named as OL including fiber attenuation and connector losses. In a point-to-point fiber link can be [12, 13]:

$$OL = 2\left(N\,L_c + M\,L_{sp} + \alpha L_f\right),\ dB \qquad (4)$$

Where NL_c is the connector loss with N connectors; ML_{sp} is the splicing loss with M splices, and α is the fiber attenuation in dB/km. The OL could, however, be very large with passive optical networks (PON) despite their attractiveness [12, 13]. The power is lost every time the power is split can be computed as follows:

$$OL = 2\left(N\,L_c + M\,L_{sp} + S\,L_{split} + \alpha L_f\right),\ dB \qquad (5)$$

Where there are S splitters each with loss L_{split}.

III. 3. TRANSMISSION CAPACITY of ROF SYSTEMS

A) SOLITON TRANSMISSION TECHNIQUE

The idea of soliton transmission is to guide the nonlinearity to the desired direction and use it for our benefit. When soliton pulses are used as an information carrier, the effects of dispersion and nonlinearity balance each other and thus don't degrade the signal quality with the propagation distance. In addition, the unique features of soliton transmission can help to solve the problems of data transmission, because the soliton data looks essentially the same at different distances along the transmission, the soliton type of transmission is especially attractive for all-optical data networking. Moreover, because of the high quality of the pulses and return-to-zero (RZ) nature of the data the soliton data is suitable for all-optical processing. In any infinitesimal segment of fiber, dispersion on one hand and non linearity of the refractive-index on the other hand produce infinitesimal modulation angles which exactly compensate reciprocally. In the sense that their sum is an irrelevant constant phase shift. Under such conditions the pulse shape is the same everywhere. All this provided that a soliton waveform be used with a peak power [14, 15]:

$$P_1 = \frac{\Delta\lambda^3\,\varphi\,A_{eff}}{4\pi^2 c\,n_{nl}\,t_0^2}, \qquad (6)$$

Where n_{nl} is the nonlinear Kerr coefficient, 2.6 x 10^{-20} m^2/Watt, Δλ is the spectral line width of the optical source in nm, P_1 is the peak power in watt, A_{eff} is the effective area of the fiber in µm^2, φ is the first order dispersion. Then the total pulse intensity width in psec is:

$$t_0 = \sqrt{\frac{\Delta\lambda^3\,\varphi\,A_{eff}}{4\pi^2\,P_1\,n_{nl}\,c}},\quad p\sec \qquad (7)$$

Then the Soliton transmission bit rate per optical network channel or unit is given as follows [16]:

$$B_{rsc} = \frac{1}{10\,t_0} = \frac{0.1}{t_0},\ Tbit/\sec/\,channel \qquad (8)$$

Then the Soliton transmission bit rate per link is given as:

$$B_{rsl} = \frac{0.1\,.\,N_{link}}{t_0},\quad Tbit\ /\sec/\ link \qquad (9)$$

In the system model analysis, the transmitted channels per link is given by:

$$N_{ch/Link} = \frac{N_{cht}}{N_L}, \qquad (10)$$

Where N_{Link} is the total number of links in the fiber cable core, and N_{cht} is the total number of channels per fiber cable core. The available soliton transmitted bit rate B_{rs} is compared as the fiber cable length, L, and consequently the soliton product P_{rsc} per channel is computed as the following expression:

$$P_{rsc} = B_{rsc}\,.\,L_f,\ Tbit.km/\sec \qquad (11)$$

Also, the soliton product P_{rsl} per link is computed as the following expression:

$$P_{rsl} = B_{rsl}\,.\,L_f,\ Tbit.km/\sec \qquad (12)$$

B) MTDM TRANSMISSION TECHNIQUE

To achieve a high data transmission bit rate in the telecommunication field is the goal of wavelength division multiplexing technology. The maximum bit rates are determined by numerous factors, including the signal modulation rate, the transmission bandwidth through the transmission media, and the response time of the optoelectronic devices. In a network, the DWDM system is simply one part of the transmission regime. Therefore, the total pulse broadening due to the first order dispersion in standard single mode fiber (SSMF) that limits the bit rates in system based DWDM communication can be[17]:

$$\Delta\tau = \varphi.\,\Delta\lambda_s\,.\,L_f,\ p\sec/mm.km \qquad (13)$$

The pulse broadening of grating-based DWDM imposes inherent limitations on the transmission bit rates. Then the MTDM transmission bit rate per channel is given by [18]:

$$B_{rmc} = \frac{1}{4\Delta\tau} = \frac{0.25}{\Delta\tau},\ Tbit/\sec/\,channel \qquad (14)$$

Then the MTDM transmission bit rate per link is given as:

$$B_{rml} = \frac{0.25\,.\,N_{link}}{\Delta\tau},\quad Tbit/\sec/\,link \qquad (15)$$

The available MTDM transmitted bit rate B_{rm} is compared as the fiber cable length, L, and consequently the MTDM product P_{rmc} per channel is computed as [19]:

$$P_{rmc} = B_{rmc}\,.\,L_f,\ Tbit.km/\sec \qquad (16)$$

Also, in the same way, the MTDM product P_{rml} per link is computed as the following expression:

$$P_{rml} = B_{rml}\,.\,L_f,\ Tbit.km/\sec \qquad (17)$$

C) SDM TECHNIQUE

We have modeled and investigated parametrically the basic MTDM and Soliton transmission techniques to transmit 100-600 optical channels based on wavelength division multiplexing (DWDM), in the interval of 1 up to 1.5 mm wavelengths. For the reality from the points of view of the spectral dependences of the different fiber characteristics [20], we employ also the space division multiplexing where 100-600 channels are divided into subgroups each subgroup has its own spectral characteristics. With total number of links, N_L= {4, 5, 6, 7, 8, 9,..24} Links. With JS={1, 2, 3, 4, 5,…......…………………..……….N_L}.

Where: $\Delta\lambda_L = \Delta\lambda / N_L \equiv Link\ spacing$ (18)

$$\delta\lambda_s = \Delta\lambda_s / (N_{ch} \cdot N_L) = \Delta\lambda_L / N_{cht} \qquad (19)$$

Where N_{ch} is the number of transmitted optical channels per optical link, N_L is the total number of optical links per fiber cable core, and $\Delta\lambda_s = \lambda_f - \lambda_i$ =0.5 mm.

IV. SIMULATION RESULTS

The following numerical data of the set of assumed affecting parameters of our suggested model are shown in Table 1 have been employed to obtain the transmission performance characteristics of ROF systems in local area optical communication networks (LAOCN) as the following operating parameters. Based on the set of the Figs. (2-17), the following facts are assured as the following results:

i) Fig. 2 has demonstrated that as fiber link length increases, total optical losses also increase at the constant number of connectors, splices, and splitters. Moreover as number of connectors, splices, and splitters increase, total optical losses also increase at the constant fiber link length.

ii) As shown in Fig. 3 has indicated that as fiber length increases, total optical losses also increase at the constant radio frequency. Also, as radio frequency increases, total optical losses increase at the constant fiber link length.

Table 1: Proposed operating parameters for our suggested ROF transmission systems.

Operating parameter	Definition	Value and units
T	Ambient temperature	$300\ K \le T \le 340\ K$
Δn	Rrefractive-index difference	0.007
N_L	Number of optical links	$4 \le N_L \le 24$
N_{cht}	Number of channels	$100 \le N_{cht} \le 600$
f_{RF}	RF operating frequency	$200 \le f_{RF}$, GHz ≤ 300
λ_s	RF signal operating wavelength	$1\ mm \le \lambda_s \le 1.5\ mm$
L_f	Fiber link length	$2\ Km \le L_f \le 20\ Km$
P_0	Optical power	$0.2 \le P_0$, Watt ≤ 0.597
n_2	Refractive index of cladding	1.445
A_{eff}	Effective area of fiber	85 μm^2
$\Delta\lambda$	Spectral width of optical source	0.1 nm
α at λ=1.55 μm	fiber attenuation	0.2 dB/km
N	Number of connectors	$4 \le N \le 32$
L_c	Connector loss	0.3 dB/km

iii) Figs. (4, 5) have proved that as number of links in the fiber cable core increases, both MTDM and Soliton bit rate per channel also increase at the

iv) constant number of transmitted channels. But as number of transmitted channels decreases, both MTDM and Soliton bit rate per channel increase at constant number of links in the fiber cable core.

v) As shown in Figs. (6, 7) have assured that as number of links in the fiber cable core increases, both MTDM and Soliton bit rate per link also increase at the constant number of transmitted channels. But as number of transmitted channels decreases, both MTDM and Soliton bit rate per link increase at constant number of links in the fiber cable core.

vi) Figs. (8, 9) have indicated that fiber link length increases, both MTDM and Soliton product per channel increase at the constant number of links in the fiber cable core. Moreover, as number of links in the fiber cable core increases, both MTDM and Soliton product per channel at the constant fiber link length.

vii) As shown in Figs. (10, 11) have proved that fiber link length increases, both MTDM and Soliton product per link increase at the constant number of links in the fiber cable core. Moreover, as number of links in the fiber cable core increases, both MTDM and Soliton product per link at the constant fiber link length.

viii) Figs. (12, 13) have demonstrated that as fiber temperature increases, both MTDM and Soliton bit rate per channel decrease at constant fiber link length. Also as fiber link length increases, both MTDM and Soliton bit rate per channel decrease at constant fiber temperature.

ix) Figs. (14-17) have demonstrated that as the fiber length increases, the soliton and MTDM product either per link or per channel also increase at constant temperature. But as temperature increases, the soliton and MTDM product decrease at constant fiber length.

x) As shown in the series of Figs. (4-17), Soliton transmission technique presents higher transmission bit rates and products either per link or per channel than MTDM transmission technique.

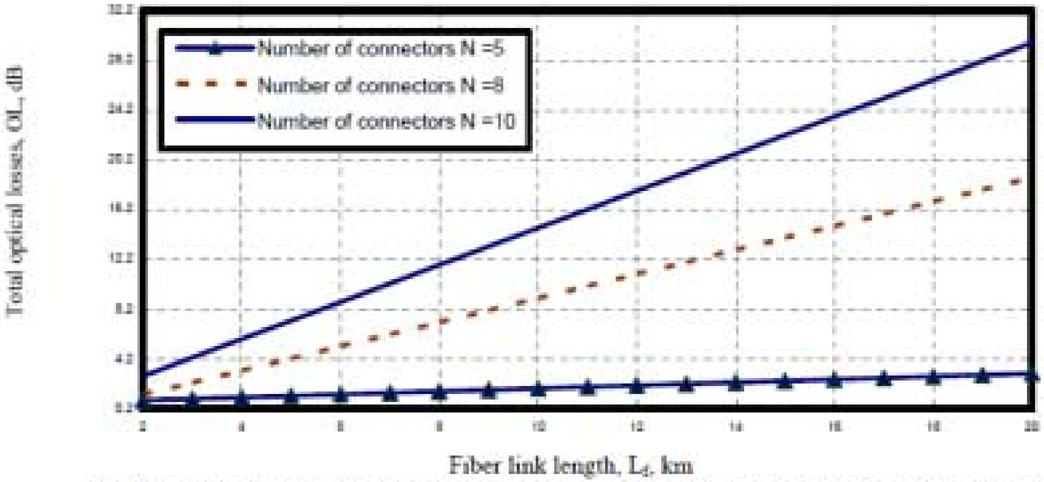

Fig. 2. Variations of total optical losses against fiber link length at the assumed set of parameters.

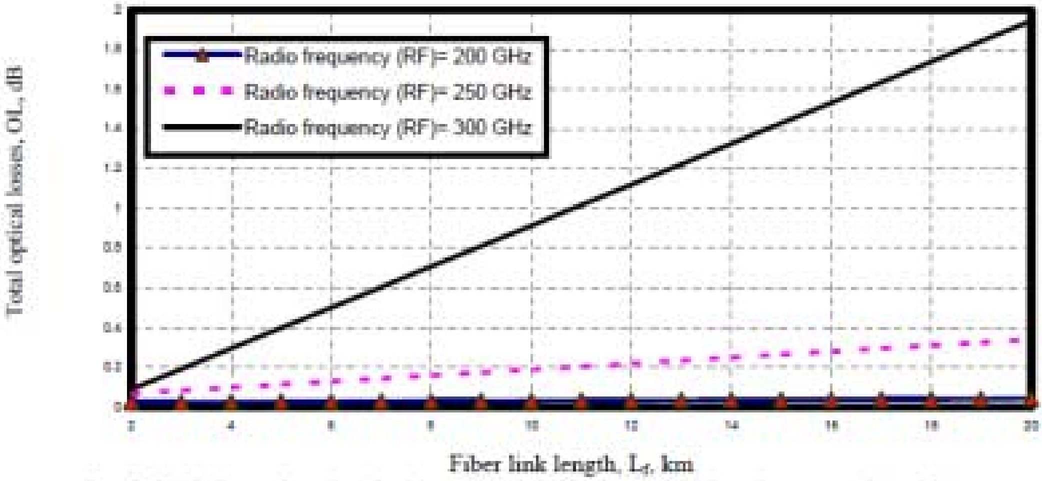

Fig. 3. Variations of total optical losses against fiber link length at the assumed set of parameters.

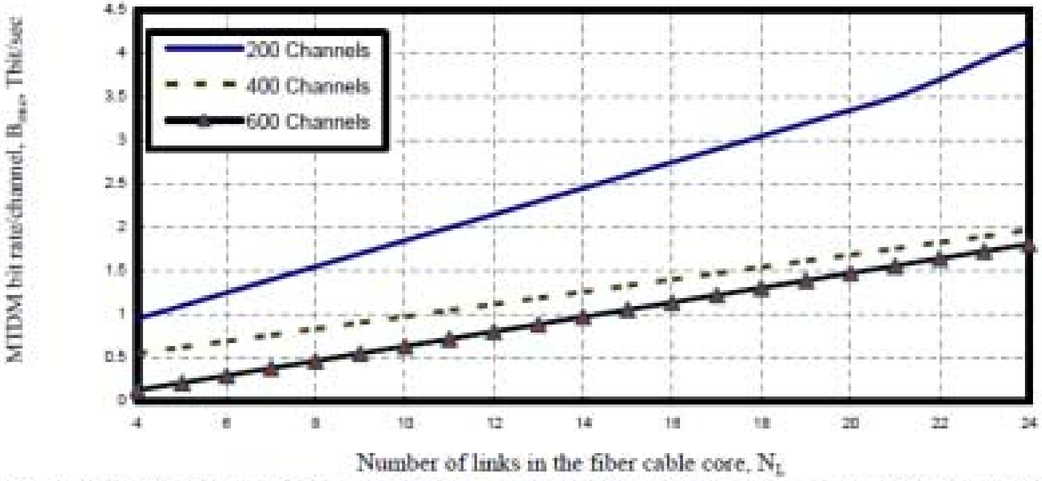

Fig. 4. Variations of MTDM bit rate per channel against number of links at the assumed set of parameters.

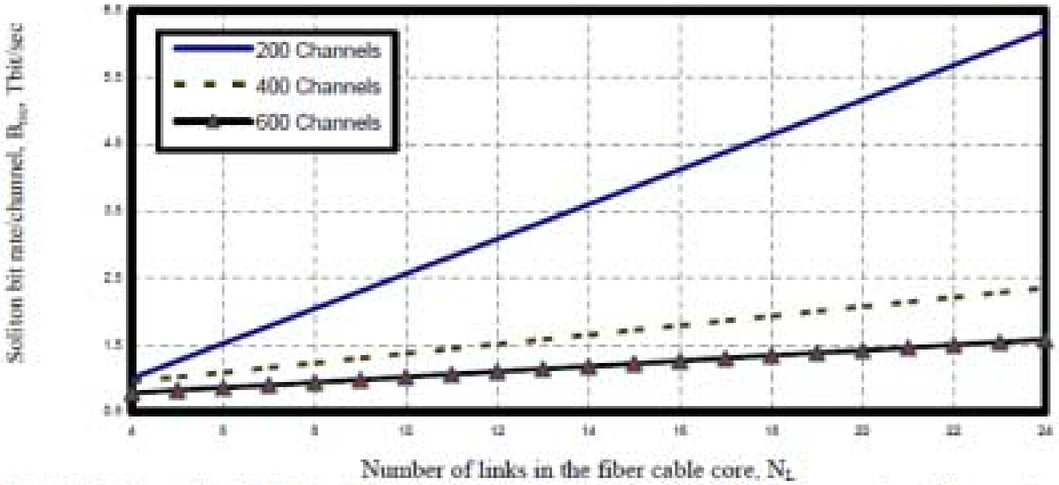

Fig. 5. Variations of soliton bit rate per channel against number of links at the assumed set of parameters.

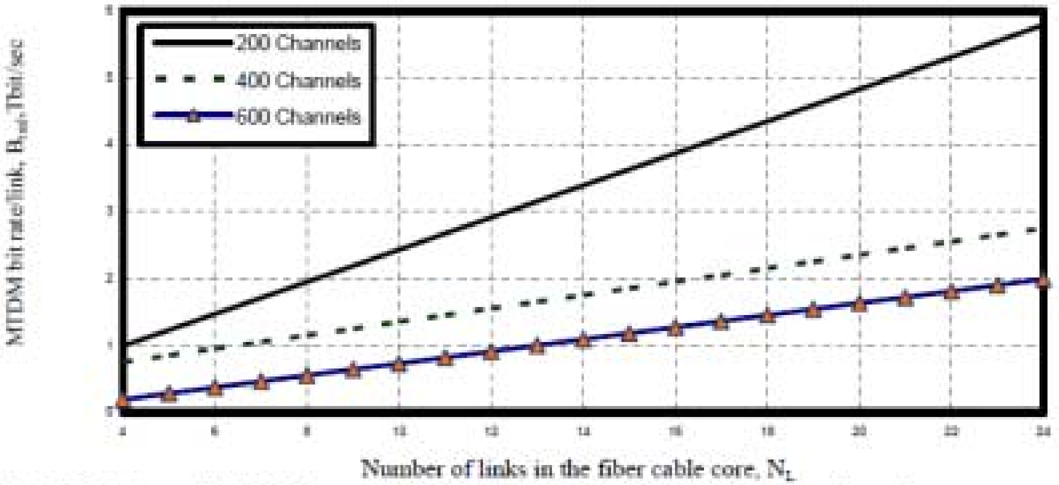

Fig.6. Variations of MTDM bit rate per link against number of links at the assumed set of parameters.

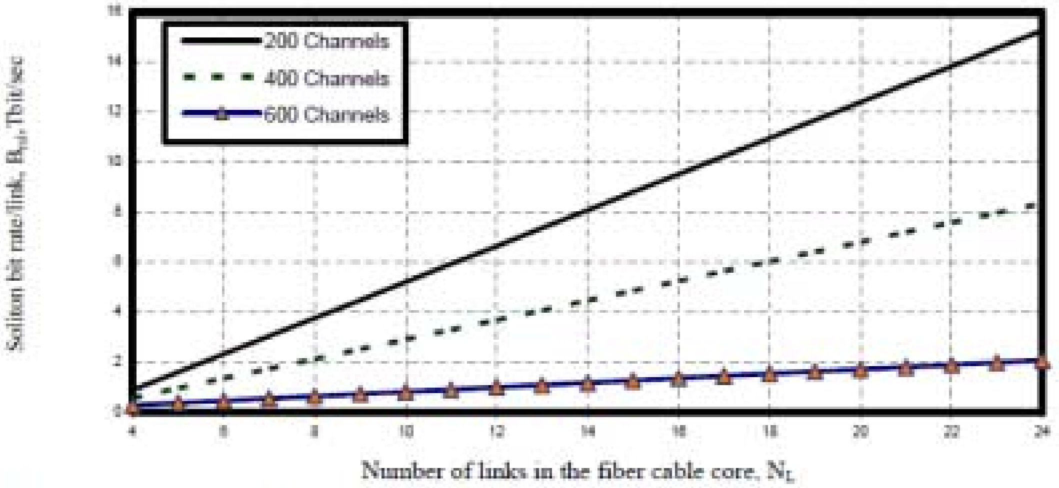

Fig. 7. Variations of soliton bit rate per link against number of links at the assumed set of parameters.

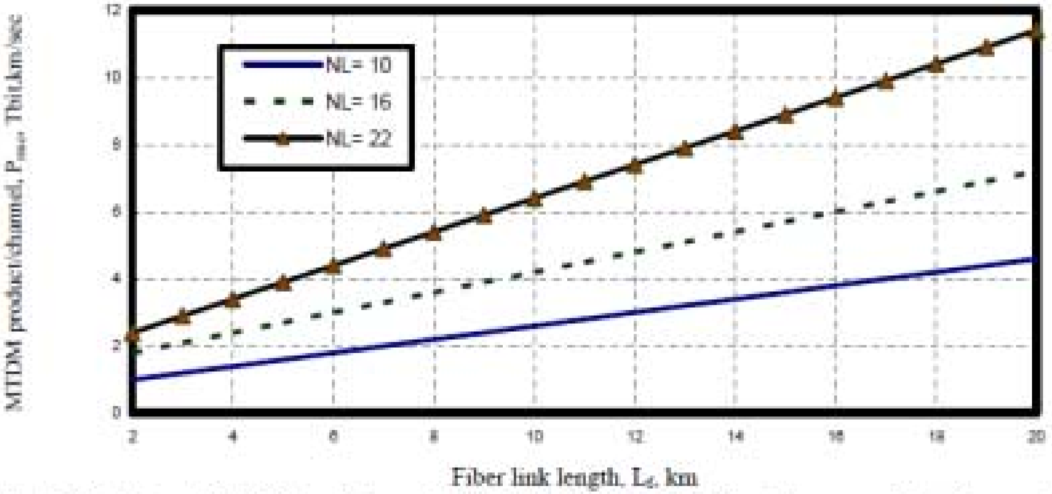

Fig. 8. Variations of MTDM product per channel against fiber link length at the assumed set of parameters.

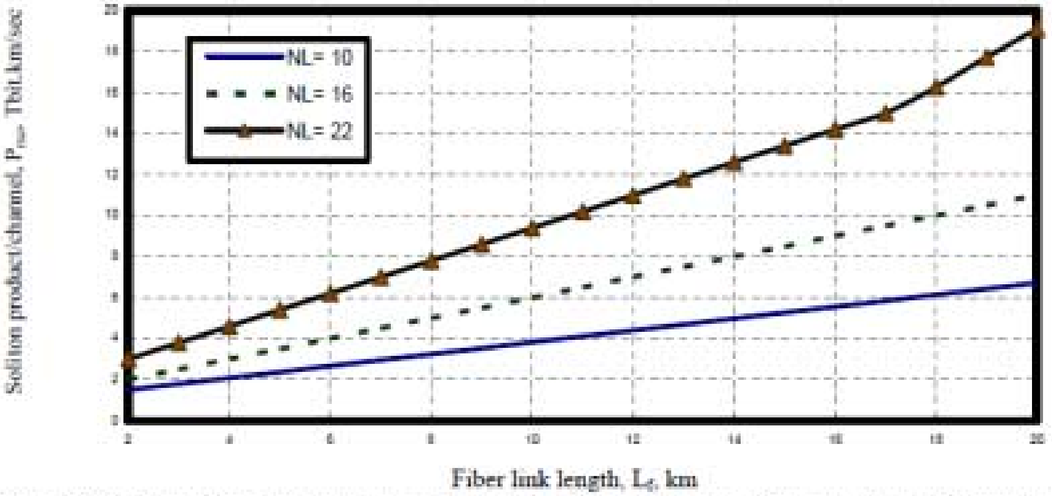

Fig. 9. Variations of soliton product per channel against fiber link length at the assumed set of parameters.

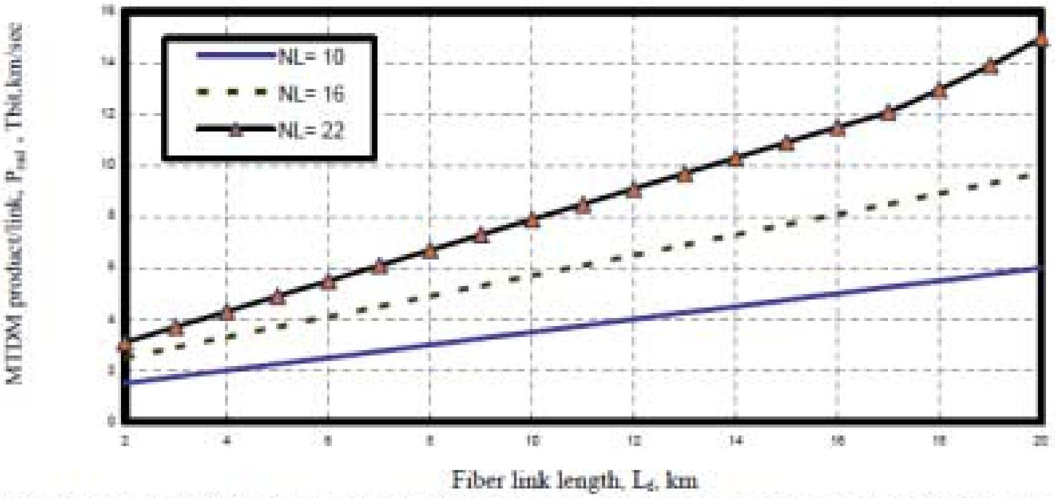

Fig. 10. Variations of MTDM product per link against fiber link length at the assumed set of parameters.

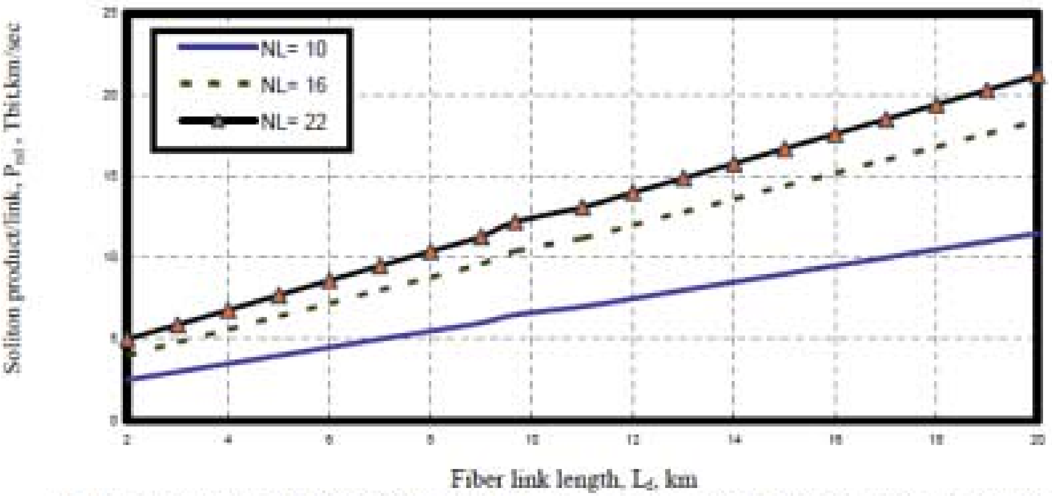

Fig. 11. Variations of soliton product per link against fiber link length at the assumed set of parameters.

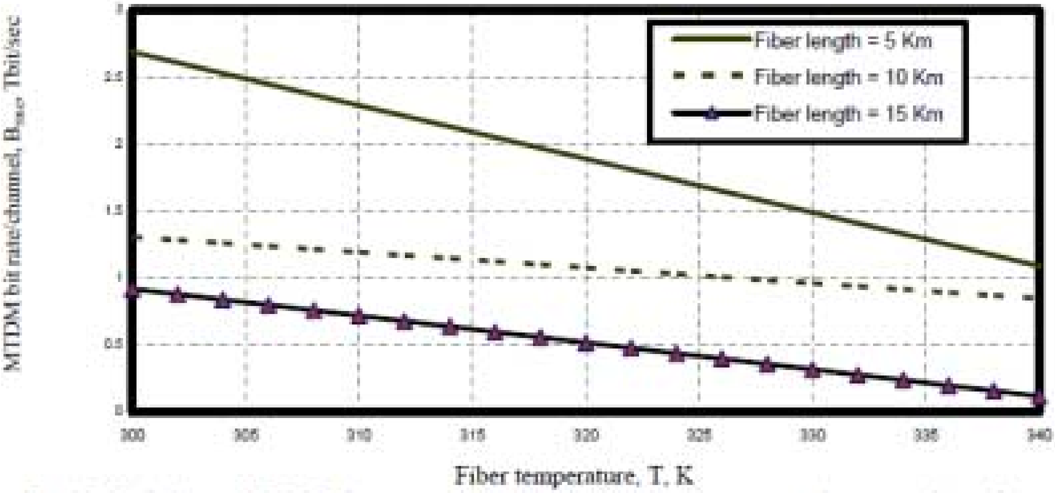

Fig. 12. Variations of MTDM bit rate per channel against fiber temperature at the assumed set of parameters.

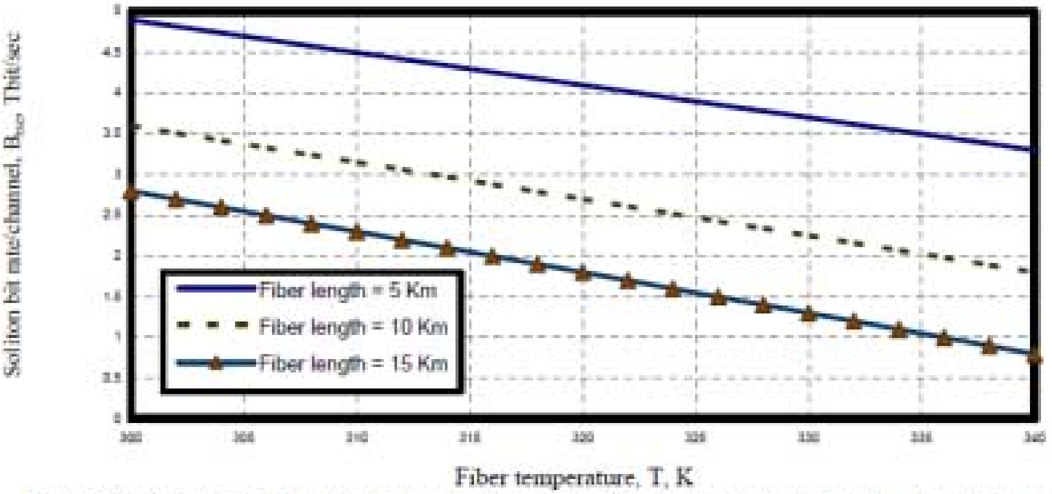

Fig. 13. Variations of soliton bit rate per channel against fiber temperature at the assumed set of parameters.

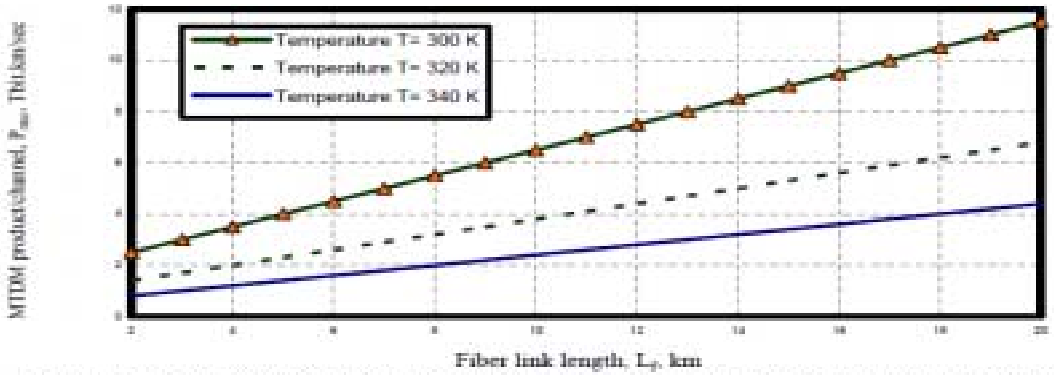

Fig. 14. Variations of MTDM product per channel against fiber link length at the assumed set of parameters.

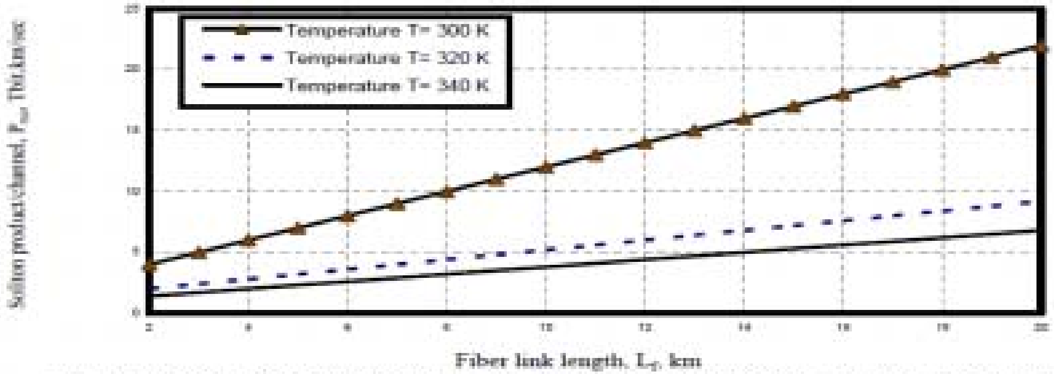

Fig. 15. Variations of soliton product per link against fiber link length at the assumed set of parameters.

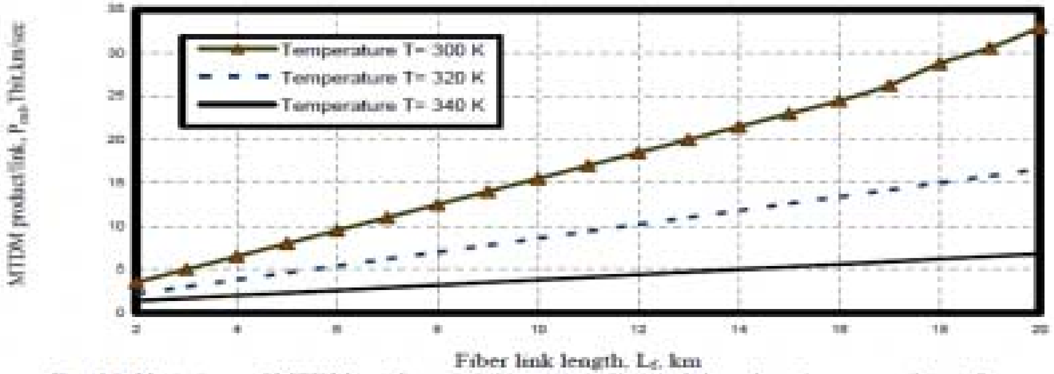

Fig. 16. Variations of MTDM product per link against fiber link length at the assumed set of parameters.

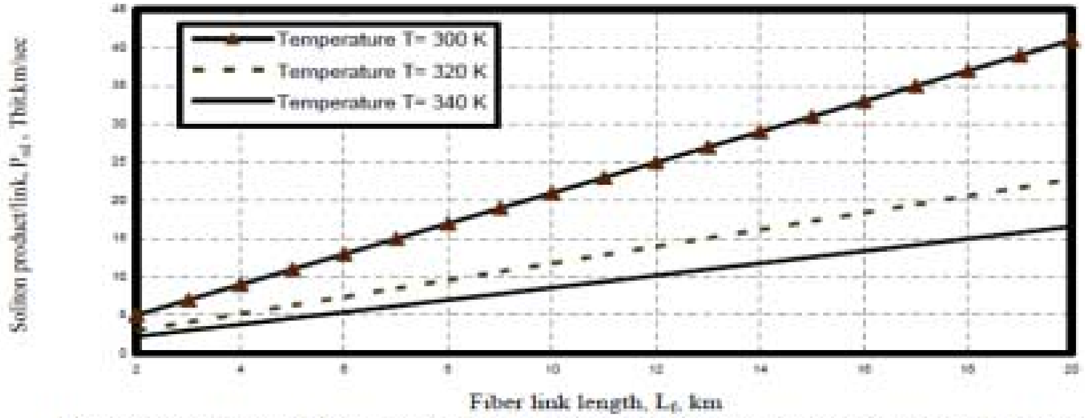

Fig. 17. Variations of soliton product per link against fiber link length at the assumed set of parameters.

V. CONCLUSION

We have been modeled and investigated ROF transmission capacity for local area optical access communication network applications within two transmission techniques named MTDM and Soliton; two multiplexing techniques named SDM and DWDM. The increased fiber link length, radio frequency, number of connectors, splices, and splitters, this lead to the increased total optical losses. The increased number of links in the fiber cable core, the decreased fiber temperature, and the decreased fiber link length, this result in the increased transmission bit rates either per optical link or per optical channel. Moreover, the increased number of links, and the increased fiber length, yields the increased MTDM and soliton product either per link or per channel. We have assured that Soliton transmission technique presents higher transmission bit rates and products either per link or per channel than MTDM transmission technique. We have compared our ROF transmission systems with simulation results as in Refs. [17, 19, 20]as shown in Table 2.

Table 2: Comparison Our ROF transmission system with Simulation results as in Refs. [17,19, 20].

	Transmission bit rates and products with ROF transmission systems	Simulation results for transmission bit rates and products as in Refs. [17, 19, 20]
	Same conditions of operation	
	- Ambient temperature T= 300 K-340 K, Number of transmitted channels= 100-600 channels, - Relative refractive-index difference Δn=0.007, Number of links in the fiber cable core N_L=4-24, - Fiber link length= 20 km, Effective area of fiber A_{eff}= 85 μm^2.	
Transmission Techniques	ROF system without amplification	Transmission Bit rates and products with backward pumping Raman amplification
Soliton bit rate/channel	3 Tbit/sec	0.088 Tbit/sec
Soliton bit rate/link	11 Tbit/sec	0.145 Tbit/sec
Soliton product/channel	19 Tbit.km/sec	0.27 Tbit.km/sec
Soliton product/link	24 Tbit.km/sec	2.6 Tbit.km/sec
MTDM bit rate/channel	3 Tbit/sec	0.028 Tbit/sec
MTDM bit rate/link	5 Tbit/sec	0.135 Tbit/sec
MTDM product/channel	11 Tbit.km/sec	0.12 Tbit.km/sec
MTDM product/link	15 Tbit.km/sec	1.2 Tbit.km/sec

It is very clear and observed from the comparison, radio over fiber transmission systems have presented the best performance, efficiency and the highest transmission bit rates and products either per link or per transmitted channel than the traditional type of optical fiber communication systems.

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