PERFORMANCE ANALYSIS OF GIGABIT-CAPABLE RADIO ACCESS NETWORKS EXPLOITING TWDM-PON AND RoF TECHNOLOGIES

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Abstract: Millimeter-wave radio-over fiber (MMW-RoF) technology is capable of exploiting both fiber communication and wireless communication to provide flexibility, long reach, high capacity, low electromagnetic interference and high immunity to the atmospheric conditions for creating next generation broadband mobile access networks. Combination of MMW-RoF systems and TWDM-PONs which are currently worldwide deployed can further reduce the cost of MMW-RoF systems due to the share of optical distributed networks. However, this may impact the system performance because RoF signals are transferred through passive optical components of TWDM-PONs. In this paper, we studied the performance of a next-generation broadband mobile access network that is based on a hybrid architecture employing TWDM-PON and MMW-RoF technologies. We have developed a mathematical model of the downlink system. We then comprehensively analyzed the performance of RoF/TWDM hybrid access downlink while considering the impacts of various physical layer impairments of both optical fiber and wireless links. The performance of RoF/TWDM-PON systems with different service reaches is also evaluated in comparison of that of corresponding traditional MMW-RoF systems. The numerical results show that the RoF/TWDM-PON combined system can take the advantages of both optical access networks and MMW-RoF technologies to create a promising low-cost, flexible gigabit-bandwidth-capable solution for next generation mobile access networks.

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I. INTRODUCTION

The explosive growth of mobile data traffic and massive increase in the number of wireless interconnected devices are exhausting the capabilities of existing wireless networks. One of the strategies to deal with the shortage of global bandwidth in wireless communications is to increase the working frequency (i.e. millimeter-wave band) and to reduce the cell size, providing higher capacity to the end users. Therefore, millimeter-wave (MMW) band has recently been proposed for future broadband cellular communication networks such as the fifth-generation (5G) mobile networks, which require thousand fold increase in the system capacity, tenfold in spectral efficiency and data rate compared to 4G mobile networks [1, 2]. However, the disadvantages of MMW frequency bands are the requirement of highly directional beam forming antennas in both mobile devices and base stations, and the short distance between transmitting and receiving antennas [1]. Hence, a larger number of cells (BSs) need to be deployed while remote cells are expected to be compact, simple and energy efficient. To achieve these requirements, complex functions such as carrier modulation and up-conversion to MMW frequency should be located at the central station (CS), and optical fibers capable of providing high data rate with low loss are considered as the most suitable medium to distribute the data-modulated millimeter-wave signals from CS to BSs. The MMW radio-over-fiber (MMW-RoF) technology combines the advantages of the both fiber communication and wireless communication to provide more flexibility, higher reach, higher capacity, lower electromagnetic interference and higher immunity to the atmospheric conditions [3, 4]. Consequently, MMW radio-over-fiber is a promising candidate to create next generation mobile access networks that are able to support ever-increasing mobile traffic and massive deployment of wireless devices in 5G networks [5, 6].

Furthermore, in order to minimize the infrastructure cost of MMW RoF systems, especially in optical domain dominated by costly deployed fibers, sharing optical distributed networks (ODNs) with other access technologies recently attracts a lot of research interests [7-10]. The most popular and widely used ODNs are that of passive optical networks. Among optical access technologies, Time and Wavelength Division Multiplexed Passive Optical Network (TWDM-PON), that has been developed by FSAN and has been standardized by ITU-T since 2013 [11,12], is the chosen solution of the second next-generation PON (NG-PON2). TWDM-PON consists of multiple XG-PONs (10-Gigabit-capable PONs) stacked onto a common optical distribution network (ODN) employing different wavelengths [11]. TWDM-PON exploits both TDM-PON and WDM PON, and provides many inherent advantages including statistical sharing of bandwidth (flexible bandwidth provision with the range from several Mb/s to a peak of 10 Gb/s) and backward compatibility [13]. TWDM-PONs are expected to be deployed worldwide in very near future. Therefore, combination of MMW-RoF system and TWDM-PON on the same optical infrastructure, i.e. reusing conventional ODNs, can help to reduce the implementation cost and complexity while offering various bandwidth flexible services for next generation broadband access networks. On our best knowledge, there is no specific paper on RoF over TWDM-PON system yet while several works on RoF/WDM-PON systems have been introduced [7-10], however, those works concentrated only on the experiment setup and analysis of optical link and the impact of wireless link was almost neglected.

In this paper, to investigate the feasibility of the RoF/TWDM-PON access networks and obtain useful information for network design, we comprehensively analyze the performance of a RoF/TWDM-PON downlink under the effects of various physical layer impairments in both optical domain and wireless domain such as different sources of noise, chromatic dispersion, and fading. We also compare the performance of RoF/TWDM-PON systems to that of conventional RoF system with dedicated single-mode fibers.

The rest of this paper is structured as follows. Section II demonstrates the downlink architecture of a TWDM-PON/RoF hybrid mobile access network. Performance analysis will be performed in Section III. Section IV presents the numerical results and discussion. Finally, our conclusions will be given in Section V.

II. PROPOSED RoF/TWDM-PON DOWNLINK SYSTEM FOR MOBILE ACCESS NETWORK

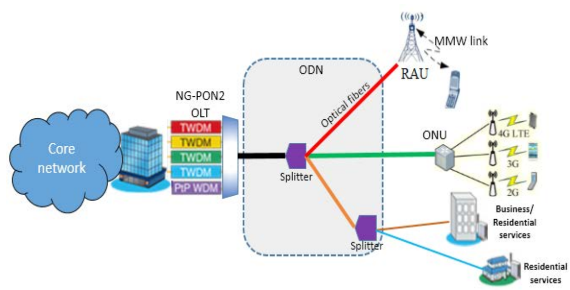
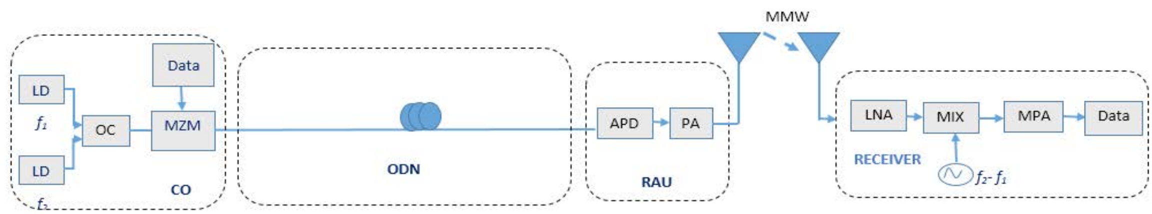
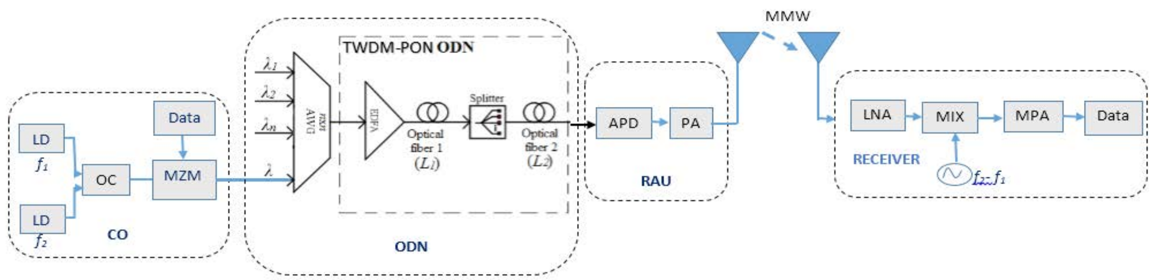


Fig. 1. RoF/TWDM-PON hybrid mobile access network

Figure 1 shows a typical architecture of flexible broadband mobile access networks based on TWDM-PON and MMW-RoF technologies which we consider in this work. The RoF/TWDM-PON combined network consists of optical fiber part (TWDM-PON) and MMW link part. TWDM-PON stacks 10 Gbit/s-capable passive optical networks via multiple pairs of wavelengths to improve the total data rate. Each XG-PON system offers the access rates of 10 Gbit/s for downstream link and 2.5 (or 10) Gbit/s for upstream link [12].



a, A downlink architecture of MMW-RoF mobile access network



b, TWDM-PON/MMW RoF downlink system

Fig. 2. a, A downlink architecture of MMW-RoF mobile access network
b, TWDM-PON/MMW RoF downlink system

Typical TWDM-PON system with four pairs of wavelengths is able to provide 40 Gbit/s and 10/40 Gbit/s in downstream and upstream, respectively. Besides, the hybrid system utilizes high capacity MMW wireless link in the distribution links for the first-mile access to support multiple users at very high bit rate.

Principally, MMW-RoF system consists of three main subsystems, including center office (CO), optical distribution network (ODN), and base stations (BS/RAU). CO performs many complex functions such as modulation, demodulation, and millimeter-wave carrier generation. In contrast, BS must be kept simple because of the large number of BSs required. CO communicates with the BSs via the ODN. Different from the ODN of traditional MMW-RoF system that is single mode fibers, the ODN is shared between RoF system and TWDM-PON system or in other words, RoF signals must traverse TWDM-PON components including multiplexer/demultiplexer (AWG), power splitters/couplers and amplifiers. A downlink architecture of MMW-RoF mobile access network is presented in Figure 2a, while the downlink model of a RoF/TWDM-PON system for broadband mobile network is shown in Figure 2b.

In the MMW-RoF system in Figure 2a, two optical carriers (f_1 and f_2) are combined at an optical coupler (OC), and then are modulated with data signal at Mach-Zehnder modulator (MZM). The modulated optical signal is transmitted via an optical fiber to base station, where an avalanche photodiode (APD) is used to convert it to electrical signal. At the output of APD, millimeter-wave is generated due to the mixing of two optical carriers, where $f_{mm} = f_2 - f_1$. Theoretically, the millimeter-wave signal will be filtered, amplified, and fed to the antenna to broadcast in the air. However, for the sake of simplicity, the filter is not shown in the figure. At the receiver, the received signal will be amplified by low noise amplifier (LNA) before multiplied with signal from oscillator, whose frequency is f_{mm}. Finally, the data signal is obtained after passing to the medium power amplifier (MPA), and the band pass filter (BPF).

On the other hand, in the Figure 2b, the signal from CO is passed on one input of AWG to multiplex with other optical signals. The signals after AWG then are amplified by EDFA and transmitted via an optical fiber 1. The splitter is located at the end of optical fiber 1 to split the signals into different branches. The optical signal from CO is continuously transmitted via the optical fiber 2 to the RAU, where an avalanche photodiode (APD) is used to convert it to electrical signal. Then, MMW signal (fmm) is generated at the output of APD, because of the mixing of two optical carriers ($f_{mm} = f_2 - f_1$). In theory, the MMW signal should be filtered, amplified, and fed to the antenna to broadcast in the air. The received signal at receiver is first amplified by a low noise amplifier (LNA). Next, a mixer (MIX) is used to multiply the amplified signal with the local signal (fmm), to down-convert the MMW signal to the data signal. Finally, signal from the MIX is passed to a medium power amplifier (MPA) and a band pass filter (BPF) to recover the data signal.

III. PERFORMANCE ANALYSIS

In this section, the performance of RoF/TWDM-PON hybrid access networks (Figure 2b) will be examined at receiver.

The two optical carriers after OC are modulated with QPSK data signal at the MZM which has modulation index of *m*, resulting in following signal

$$E(t) = \left[\sqrt{P_s}(\cos\omega_1 t + \cos\omega_2 t)\right]\left[1 + mS(t)\right], \quad (1)$$

where P_s is transmitted power at the CO, $\omega_{1,2}$ are the angular frequencies of the signals from two laser diodes (LDs), and $S(t)$ is the QPSK data signal.

The signal is directed to one input of AWG. The output of AWG given by

$$E_T(t) = \sum_{i=1}^{N_c} E_i(t) * h_i^{T_x}(t), \quad (2)$$

where, $E_i(t)$ is the input i^{th} signal of the AWG and $h_i^{Tx}(t)$ is the transfer function of the AWG for the i^{th} channel.

When the optical signal passes through the EDFA, the output signal is given by

$$E_A(t) = \sqrt{G_E}\, E_T(t) + n_{ASE}(t), \quad (3)$$

where G_E is the gain of EDFA and n_{ASE} is the ASE noise which can be determined by

$$\left\langle n_{ASE}^2 \right\rangle = P_{ASE} = 2n_\varsigma h_0 \left(G_E - 1\right) B_0. \quad (4)$$

The signals after EDFA are transmitted via the optical fiber 1 to splitter with the splitting ratio of N_s, then transferred via the optical fiber 2 to RAU. Considering the fiber loss and dispersion, the optical signal received at RAU can be expressed as

$$E_r(t) = \sqrt{\frac{G_E}{N_s}}\sqrt{P_r}(\cos\omega_1 t + \cos\omega_2 t)\left[1 + mS(t)\right], \quad (5)$$

where P_r is the optical power received at RAU, in which $P_r = P_s \exp(-\alpha L_1 - \alpha L_1) h_{CD1} h_{CD2}$, where α is fiber attenuation coefficient, L_1 is the length of optical fiber between the EDFA and splitter and L_2 is the length of optical fiber between the splitter and RAU. h_{CD1} and h_{CD2} are the decrease in signal power due to the chromatic dispersion, which are given by [14,15]

$$h_{CD1} = \exp\left(-2\pi\Delta\upsilon_m \Delta\tau_1\right), \quad (6)$$

$$h_{CD2} = \exp\left(-2\pi\Delta\upsilon_m \Delta\tau_2\right), \quad (7)$$

where $\Delta\upsilon_m$ is the full width at half maximum (FWHM) of the laser power spectrum, $\Delta\tau_1$ and $\Delta\tau_2$ are the differential propagation delay of two optical signal because of chromatic fiber dispersion, which are given by

$$\Delta\tau_1 = DL_1 \frac{\lambda^2}{c} f_c, \quad (8)$$

$$\Delta\tau_2 = DL_2 \frac{\lambda^2}{c} f_c, \quad (9)$$

where D represents the fiber dispersion parameter; c is the velocity of light in vacuum; λ is wavelength and f_c is the offset frequency (i.e., MMW frequency).

Consequently, the photocurrent after the APD could be presented as

$$\begin{aligned} I(t) &= RM\left|E_r(t)\right|^2 \\ &= RMP_r \frac{G_E}{N_s}\left[\cos^2(\omega_1 t) + \cos^2(\omega_2 t) + 2\cos(\omega_1 t)\cos(\omega_2 t)\right]\left[1 + mS(t)\right]^2 \\ &= RMP_r \frac{G_E}{N_s}\left[1 + \frac{1}{2}\cos(2\omega_1 t) + \frac{1}{2}\cos(2\omega_2 t) + \cos(\omega_1 + \omega_2)t + \cos(\omega_1 - \omega_2)t\right]\left[1 + mS(t)\right]^2, \end{aligned} \quad (10)$$

where $\Re$ is the responsivity and M is the multiplication factor of the APD. From (10), the term $\cos(\omega_1-\omega_2)t$, which is the MMW signal, could be extracted by using a band pass filter. Therefore, the current of MMW signal should be expressed as

$$I_{mmw}(t)=\Re MP_r\frac{G_E}{N_s}\left[\cos(\omega_1-\omega_2)t\right]\left[1+mS(t)\right]^2 \quad (11)$$

Next, the MMW signal will be amplified, fed to the antenna and broadcasted to the receivers. At the receiver, the received signal is passed to the LNA and mixer. At the mixer, the signal is multiplied with the local signal (f_{mm}) from oscillator resulting the signal can be written as

$$I_{mix}(t)=\frac{\Re MP_rG_E\sqrt{\frac{G_PG_{Tx}G_{Rx}G_L}{P_LL_I}}}{2N_s}\left[1+\cos2(\omega_1-\omega_2)t\right]\left[1+2mS(t)+m^2S(t)^2\right], \quad (12)$$

where G_{Tx} and G_{Rx} are the transmitting and receiving antenna gains; G_P and G_L are the power gains of PA and LNA, respectively; L_I is the antenna implementation loss; P_L is the total wireless link path loss.

For MMW link, LOS communication and a high-gain directional antenna are required [16,17]. Besides, in outdoor scenarios, antennas are usually mounted on roofs or high elevated masts, where are close to free space environment. Therefore, the MMW link mostly suffers from path loss, atmospheric absorption, and rain attenuation [16]-[21]. Consequently, the total path loss of MMW link can be expressed in decibel as

$$P_L=P_{fs}+P_{at}+P_{rain}=20\log\frac{4\pi df_{mm}}{c}+\left(\gamma_{ox}+\gamma_{wv}+\gamma_{rain}\right)d, \quad (13)$$

where P_{fs} is free space path loss, P_{at} is atmospheric absorption that includes oxygen and water vapour absorption, and P_{rain} is the attenuation due to rain. Next, d is the distance of wireless link, f_{mm} is the frequency of MMW carrier, and c is the speed of light in vacuum. Lastly, γ_{ox}, γ_{wv}, and γ_{rain} are the attenuation coefficient of oxygen, water vapor, and rain, respectively.

The DC component, second harmonic, and the frequency of $2(\omega_1-\omega_2)$ from (12) will be eliminated after the BPF. As a result, the data signal is obtained as

$$I_{rec}(t)=\frac{\Re MP_rG_E}{N_s}\sqrt{\frac{G_PG_{Tx}G_{Rx}G_LG_M}{P_LL_I}}\left[mS(t)\right], \quad (14)$$

where G_M is the MPA power gain.

Next, we will calculate the total noise variance, which is contributed from various types of noise including laser intensity noise (RIN), phase noise, amplifier noise, and receiver noise [18, 22, 23]. The noise variance without phase noise is given by

$$\sigma_N^2=2\,q\,M^2F_A(\Re P_r+I_d)\,B_n+\frac{4\,K\,T\,B_n}{R_L}F_n+2RIN\Re^2M^2P_r^2B_n+\sigma_{ASE}^2, \quad (15)$$

where q is the electronic charge, B_n is the effective noise bandwidth, I_d is the dark current, K is the Boltzmann constant, T is the temperature of the receiver, R_L is the load resistance, F_n is the noise figure of the PA, σ_{ASE}^2 is the EDFA noise, and F_A is the excess noise factor of the APD. F_A is given by [22]

$$F_A(M)=k_AM+(1-k_A)(2-1/M), \quad (16)$$

where k_A is the ionization-coefficient ratio.

The presence of ASE results in three kinds of noises, including the ASE shot noise, the signal-spontaneous beat noise, and the spontaneous-spontaneous beat noise. Therefore, the total noise caused by EDFA can be expressed as

$$\sigma_{ASE}^2=\sigma_{ase-sh}^2+\sigma_{s-sp}^2+\sigma_{sp-sp}^2, \quad (17)$$

where σ_{ase-sh}^2, σ_{s-sp}^2, σ_{sp-sp}^2 is the shot noise, the signal-spontaneous beat noise, and the spontaneous-spontaneous beat noise, respectively.

Under the effect of chromatic fiber dispersion, the two optical signals suffer from the differential propagation delay when they go through the two optical fibers. The delay results in the increase in phase noise on the remotely generated MMW signal. The phase noise is presented as phase variance which is written as [15]:

$$\sigma_{CD1}^2 = \int_0^{B_n} \frac{2\Delta\upsilon_m}{\pi f^2}\left\{1-\cos\left(2\pi f \Delta\tau_1\right)\right\} df \approx 2\pi\Delta\upsilon_m B_n \left(\Delta\tau_1\right)^2, \quad (18)$$

$$\sigma_{CD2}^2 = \int_0^{B_n} \frac{2\Delta\upsilon_m}{\pi f^2}\left\{1-\cos\left(2\pi f \Delta\tau_2\right)\right\} df \approx 2\pi\Delta\upsilon_m B_n \left(\Delta\tau_2\right)^2, \quad (19)$$

Consequently, the total noise variance can be written as

$$\sigma_{TN}^2 = \sigma_N^2 + \sigma_{CD1}^2 + \sigma_{CD2}^2. \quad (20)$$

At the receiver, the total amplifier noise figure can be written as [23]

$$NF_{Amp} = NF_{LNA} + \left(\frac{NF_{MPA} - 1}{G_L}\right), \quad (21)$$

where NF_{Amp} is the total amplifier noise figure; NF_{LNA} and NF_{MPA} are the noise figures of the LNA and MPA, respectively. Therefore, based on (14), (20), and (21), the downlink *SNR* can be presented as

$$SNR = \frac{P_s}{P_N} = \frac{(\Re MmP_r)^2 \sigma_d{}^2 G_P G_{Tx} G_{Rx} G_L G_M G_E^2}{\sigma_{TN}^2 P_L L_I NF_{Amp} NF_{Rx} KTB_n N_s^2}, \quad (22)$$

where B_n is the effective noise bandwidth, K is Boltzmann's constant, T is the absolute temperature at the RF receiver, NF_{Rx} is the receiving antenna noise figure, and σ_d^2 is the power of normalized data signal.

Finally, BER will be presented as a function of SNR for the case of QPSK modulated data as follows

$$BER = \frac{1}{2} erfc\left(\sqrt{\frac{SNR}{2}}\right). \quad (23)$$

IV. NUMERICAL RESULTS

In this section, based on the performance analysis in Section III, performance, in terms of BER, of the RoF/TWDM-PON downlink will be analyzed as a function of a number of system parameters including the laser output power (P_s), total fiber length, splitting ratio, and the wireless link distance. Table I presents the system parameters and constants used in our analysis.

Figure 3 shows the performance comparison between the RoF/TWDM-PON hybrid access network (our proposed system) and the corresponding MMW-RoF with the total optical fiber distance (L) of 20 km, 40 km and 60 km. The obtained results confirm that, to provide the cost effective, the RoF/TWDM-PON hybrid system suffers a slight performance offset. When the transmitting power is increased, BERs of both the RoF/TWDM-PON and MMW RoF systems are reduced rapidly. The reason is that increasing the power will help to overcome the performance degradation caused by fiber chromatic dispersion and channel loss.

In order to evaluate the impact of the total optical fiber distance, L, in Figure 4, the RoF/TWDM-PON hybrid system performance is investigated versus the total optical fiber distance with different EDFA gain values. The graphs show that the system performance is degraded seriously (BER is increased fast) when the system reach, L, is extended due to the loss and impact of MMW and TWDM-PON links. The maximum total distance relies on the required BER and the amplifier gain of EDFA; longer distance can be achieved with higher amplifier gain or less BER required.

Table I. Key System Parameters

Name	Symbol	Value
Fiber attenuation coefficient	α	0.2 dB/km
Load resistance	R_l	50 Ω
PD responsivity	$\Re$	0.6 A/W
APD multiplication factor	M	40
MMW frequency	f_{mm}	60 GHz
LNA gain	G_L	3 dB
MPA gain	G_M	15 dB
PA gain	G_P	15 or 25 dB
Tx gain	G_{Tx}	20 dB
Rx gain	G_{Rx}	15 dB
Implementation loss	P_I	6 dB
EDFA gain	G_E	15 dB
Splitting ratio	N_s	64
Rx noise figure	NF_{Rx}	10 dB
Amplifier noise figure	NF_{LNA}, NF_{MPA}, F_n	4 dB
Boltzmann constant	K	1.38e-23

Name	Symbol	Value
Normalized data signal power	σ_d	1
Effective noise bandwidth	B_n	10 GHz
Full width half maximum line width of the laser	$\Delta\upsilon_m$	12.75MHz
Attenuation coefficient of oxygen	γ_{ox}	15.1 dB/km
Attenuation coefficient of water vapour	γ_{wv}	0.1869 dB/km
Attenuation coefficient of rain	γ_{rain}	dB/km

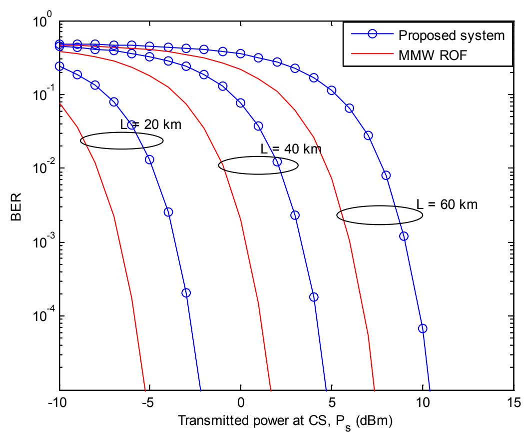


Fig. 3. Performance comparison of RoF/TWDM-PON hybrid system and MMW RoF system with G_E = 15 dB

Next, the effects of the splitting ratio and transmitted power on the system performance are demonstrated in Figure 5 As can be seen from the figure, the system performance is degraded as higher splitting ratio is applied because the splitter loss is strongly determined by the splitting ratio; the higher splitting ratio is, the greater loss is caused. That is the reason why higher transmitted power is required for greater splitting ratio.

Finally, we also analyzed the system performance against the wireless link distance (*d*). The impact of the MMW link distance on the system performance is illustrated in Figure 6. The wireless link distance, *d*, varies from 0 to 1 km, while the radio frequency is 60, 90, and 120 severally. The numerical results prove that the system performance strongly depends on both the wireless link distance and the MMW frequency; it becomes worse as the wireless link distance increases or higher MMW frequency is applied. Besides, wireless link distance affects the system performance; longer distances seriously degrade the system performance, i.e. it causes BER of the link greater than 10^{-3} with short wireless link distances (at frequency of 120 GHz and wireless link distance of 300 m). Hence, the wireless link distance should be limited to ensure the system performance.

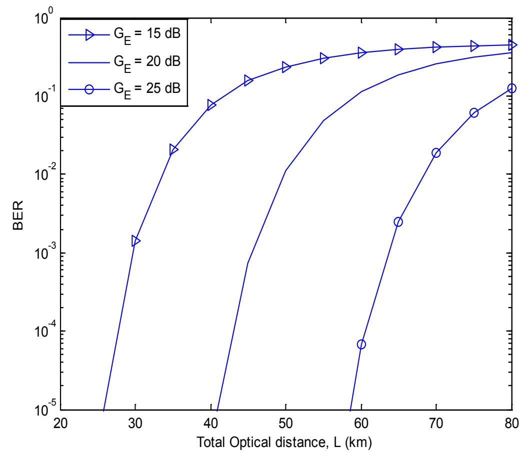


Fig. 4. Dependence of the BER performance on the total optical fiber distance (L) with P_s = 5 dBm

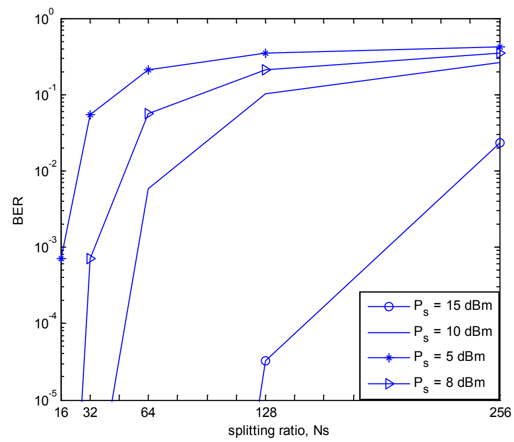


Fig. 5. Dependence of the BER performance on the splitting ratio with G_E = 15 dB and L = 40 km.

V. CONCLUSIONS

We have developed a mathematical model of a RoF/TWDM-PON downlink for next generation mobile access networks and comprehensively analyzed the performance of the flexible and gigabit-capable RoF/TWDM-PON hybrid system. Our developed model considers not only various sources of noises but also many physical impairments of optical links and wireless channels. The dependence of the system performance on the physical impairments is then thoroughly investigated. The analytical results demonstrate that the combination of TWDM-PON and MMW-RoF over the same infrastructure can provide a cost-efficient, flexible and gigabit-bandwidth-capable solution for next generation mobile access networks.

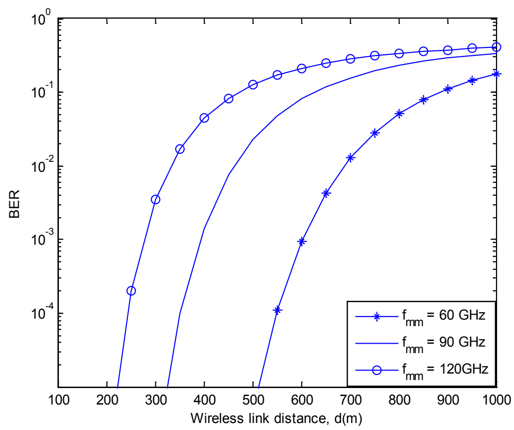


Fig. 6. Impact of the MMW link distance on BER

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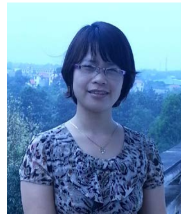

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