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Network Availability of Hybrid FSO/mmW 5G Fronthaul Network in C-RAN Architecture

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Abstract

New innovation approach called -centralized radio access network (Cloud-RAN or C-RAN) - architecture is developed to meet the explosive growth in mobile traffic in the 5th generation (5G) mobile networks especially in the need of high-speed, high capacity, real-time data, and high-reliability. In C-RAN architecture, fronthaul networks connect between the radio units called -Remote Radio Heads (RRHs)- and the processing unit called -Base Band Processing Unit (BBU)-. Recently, hybrid free space optics (FSO) and millimeter waves (mmW) network is considered to be a promising solution that can match with the requirements of 5G fronthaul networks. In this paper, hybrid FSO/mmW links at each RRH is proposed to enhance the performance of C-RAN fronthaul network at various weather conditions. The performance of hybrid FSO/mmW technology as a fronthaul network is evaluated at different weather conditions and compared to other technologies. The numerical results reveal that improvements are obtained in network reliability using hybrid FSO/mmW fronthaul network, especially at severe weather conditions.

1. Introduction

5th generation of mobile networks (5G) is the next evolution in the communications society where access to information and sharing of data is available to anyone at anyplace and anytime [1]. According to this vision, 5G aims to have [2]: (i) 1000 times higher mobile data volumes per geographical area (i.e., up to Tbps per square kilometer in some ultradense scenarios), (ii) 1000 times more connected devices (i.e., with densities that can be over a million terminals per square kilometer), and (iii) requirements for 5 times lower end-to-end service latency (i.e., with values as low as a few milliseconds). To meet these future challenges a tight integration between the 5G radio and the transport network segments is needed [3]. The wireless communication systems are increasingly calling for smart wireless network architectures to decrease networking cost and encounter the need of low power consumption. Therefore, Cloud Radio Access Network (C-RAN) is considered to be the most promising and innovated architecture for the next generation mobile and wireless communication. In C-RAN architecture, the traditional base station (BS) is divided into a centralized signal processing unit (shared) called a Baseband Processing Unit (BBU), multiples Remote Radio Heads (RRHs) deployed on site and a high speed fronthaul transport network that connects RRH to the central processing office (BBU Pool) as shown in Fig. 1.

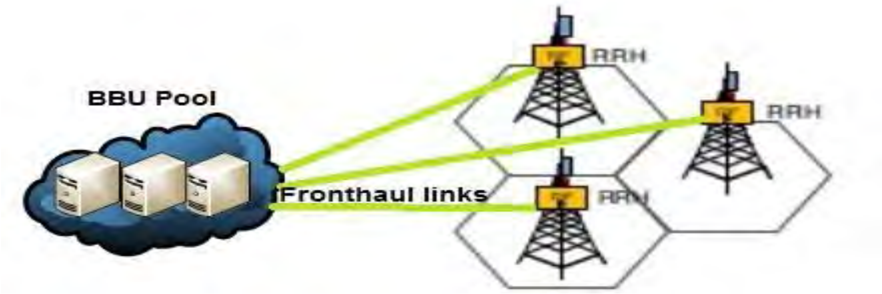

Fig. 1. C-RAN architecture [3].

The evolution of the radio access network architecture needs to be complimented by an evolution of the fronthaul transport network. There is a huge need for high capacity, high available, scalable and cost and energy effective fronthaul network that is able to forward the massive traffic to/from the large number of RRHs from/to the BBU [2].

Clearly, there are many wireless communication technologies that can be key enablers for 5G fronthaul transport networks. The first one is using Free Space Optics (FSO) as it can overcome most challenges in C-RAN fronthaul network. The advantages of FSO are it uses a licensed-free wavelength, supports full-duplex, high-speed transmission, and is immune from electro-magnetic interference. However, the network availability is decreased at the foggy weather that is considered to be drawback in the FSO systems [4]. The second one is using Millimeter Waves (mmW) which is actually the key technology within the evolution of 5G cellular networks. Unlike microwave links, mmW links cast very narrow beams that allow for deployment of multiple independent links in close proximity, Moreover, mmW also has the potential to offer bandwidth delivery comparable to that of optical fiber, but with reasonable cost. However, rainy weather could cause large attenuations in mmW links which could decrease the network availability [5].

Recently, hybrid FSO/mmW systems are considered to be a promising solution to provide wireless fronthauling services for the traffic of RRHs on C-RAN architecture. The benefits of these two emerging technologies can be used together to provide high data rates, scalable and cost efficient fronthaul system that will be suitable for 5G C-RAN requirements. The idea behind a combination between FSO and mmW is the complementary behavior of each technology during various weather conditions. Since fog and rain are the dominant causes for attenuation in the FSO and mmW links, respectively, FSO and mmW can replace or complement each other by providing nearly the same throughput requirements in data transmission when one of them fails. The switching between the two links is based on variations in the channel conditions. Obviously, the most efficient solution for high-throughput wireless connectivity is to use both FSO and mmW links simultaneously as it can increase the capacity and the availability of the fronthaul system [6].

Hybrid FSO/RF networks are used in different applications for the development of the network performance. Several studies have been proposed on hybrid FSO/RF communications systems. FSO/mmW Link switching has been proposed extensively which can categorize in two main schemes i) hard switching proposed in [7-8] that offers one link selected which can support the required QoS. This technique offers a trade-off between link availability and average data rate ii) soft switching proposed in [9] that offers the two links which are always on and rates adapted by channel coding. According to channel conditions this technique offers high availability and high-power consumption. In [10], the authors present Common Public Radio Interface (CPRI) specification, its concept, design and interfaces, and further provide a guideline to fronthaul dimensioning in realistic LTE scenarios. The characteristics of FSO and mmW are presented in [11] and [12], respectively.

In this paper, hybrid Free Space Optics and Millimeter Wave (FSO/mmW) network is proposed to be used as a fronthaul network to enhance the performance of C-RAN architecture at various weather conditions. Also, a proposed scheme for the selection / switching between FSO and mmWfronthaul links is investigated based on CPRI requirements. This proposed technique requires instantaneous knowledge of bit error rate (BER) in the FSO and mmW transmitters. In other words, full channel state information (CSI) is required. Furthermore, the performance of hybrid FSO/mmWfronthaul network is evaluated in terms of network availability at different foggy and rainy weather conditions and compared to that in all FSO and all mmW systems.

The reminder of this paper is organized as follows: In the next section, the challenges and requirements of fronthaul network in C-RAN architecture is studied. Section 3 presents channel modelling and characterization for both FSO and mmW systems. Hybrid FSO/mmWfronthaul switching criteria is investigated in section 4. Simulation results are provided in section 5. Finally, the paper is concluded in section 6.

2. Challenges of fronthaul network in C-RAN

In C-RAN architecture, Remote Radio Heads (RRHs) include the radio, the associated amplification/filtering, and the antenna. On the other side, Baseband processing Unit (BBU) is implemented separately and performs the centralized signal processing functionality of the RAN. The RRHs and BBU are connected together using fronthaul transport network. The decentralized BBU enables agility, faster service delivery, cost savings, and improved coordination of radio capabilities across a set of RRHs.Common Public Radio Interface (CPRI) is used as fronthaul interface. CPRI is the standardized interface protocol widely used for IQ data transmission between RRHs and BBUs with a constant bit-rate, whose data rates go from 614.4 Mbps up to 12.165 Gbps. The data rate of the CPRI interface is dependent on radio access technology (RAT), carrier bandwidth and Multiple Input Multiple Output (MIMO) implementation. The CPRI data-rate results from the following calculation [10]:

$$CRRI\ Data\,rate = N_A \times S_r \times N \times 2(\frac{I}{Q}) \times C_w \times C \qquad (1)$$

Where:N_A is the number of antennas per sector, S_r is the sampling rate used for digitization (sample/s/carrier), N is the sample width (bits/sample), 2(I/Q) is a multiplicationfactor for in-phase (I) and quadrature-phase (Q) data, C_w represents the factor of CPRI control word (16/15) and C is a coding factor (either 10/8 for 8B/10B coding or 66/64 for 64B/66B coding). Furthermore, the main requirements for CPRI transmission are delay and bit error rate (BER). Therefore, fronthaullink should operate with at most 5 us delay excluding propagation delay, and a maximum acceptable BER of 10^{-12}[10]. Actually, there are many challenges in the design of fronthaul network in C-RAN. The first challenge is the requirement of cost-effective and scalable networks that connect a large number of RRHs to/from the BBU, while ensuring sufficient capacity and quality of service (QoS). The second one is the availability of fronthaul transport networks to cope with different weather conditions to guarantee a better user experience with acceptable BER $\leq 10^{-12}$. Finally, reducing power consumption is also an important issue. To overcome these challenges, the benefits of FSO and mmWtechnologies can be used together in hybrid system to provide high data rates, scalable and cost efficient fronthaulnetwork suitable for C-RAN architecture.

3. Hybrid FSO/mmW link Model

The performance of hybrid FSO/mmW link relies on channel models of both FSO and mmW which experience different channel gains at the same weather conditions. FSO link is mainly affected by fog attenuation, while rain attenuation is the dominant one in mmW link.Naturally, fog and rain rarely occur concurrently and their influences can be studied separately.

3.1 FSO communication channel

Both link losses and noise can degrade the performance of FSO link. Also, the FSO link performance depends on the selected wavelength, modulation formant and transmitted power level [13]. FSO channel losses have both atmospheric and geometric losses. Atmospheric loss includes fog, rain and scintillation [14]. In FSO link modeling, the collecting aperture diameter of an optical receiver could be larger than the spatial scale of the optical scintillation that is caused by atmospheric turbulence. In this condition, the FSO receiver will average fluctuations of the received waveform over the aperture area, leading to reduced signal fluctuations, especially if the network experiences weak turbulence [15]. In this paper, the receiver diameter is assumed to be large, so that the effect of atmospheric turbulence is relatively very small compared to that caused by fog and rain attenuations [16]. Therefore, the total FSO link loss is given by:

$$A_{FSO} = A_{fog} + A_{rain} + A_{geo.} \ (dB) \qquad (2)$$

Among all atmospheric losses, fog is the dominant cause of attenuation in FSO link. Using Kim model, for accurate prediction at low visibility values, the fog attenuation is given as [11]:

$$A_{Fog} = 10 \times \log\ (\exp(\alpha \times L)) \ (dB) \qquad (3)$$

Where, α is total extinction coefficient, and is defined by:

$$\alpha = \frac{13}{V}\left(\frac{\lambda}{\lambda_o}\right)^{-q}\left(\frac{dB}{Km}\right) \ (4)$$

Where, V is the visibility in kilometers, λ is the wavelength in nanometers, λ_o is 550 nm, L is the distance in kilometers and q is the distribution of scattering particle size and is described by:

$$q = \begin{cases} 1.6 & \text{if } V > 50 \text{ Km} \\ 1.3 & \text{if } 6 \text{ Km} < V < 50 \text{ Km} \\ 0.16\,V + 0.34 & \text{if } 1 \text{ Km} < V < 6 \text{ Km} \\ V - 0.5 & \text{if } 0.5 \text{ Km} < V < 1 \text{ Km} \\ 0 & \text{if } V < 0.5 \text{ Km} \end{cases} \qquad (5)$$

From equation (5), at $V < 0.5$ km, fog particle sizes are much larger than the FSO wavelength. As a result, the scattering particles are large enough that the angular distribution of scattered radiation can be described by geometric optics. Therefore, based on Mie scattering theory calculations, the proposed Kim model considered fog attenuation for $V < 0.5$ km as wavelength independent [17].

Generally, rain attenuation in FSO links is smaller than that caused by fog. This occurs because the rain droplet size is relatively larger than the used wavelength of the optical signal ($\lambda = 1500$ nm). The rain attenuation is calculated using Japanese empirical model as [17]:

$$A_{Rain} = 1.076\, R^{0.67} \times L \qquad (dB) \tag{6}$$

Where,R is the rainfall rate in mm/hr.

Even at clear weather, geometric loss occurs due to the divergence of the optical beam over its propagation distance. The geometric Loss is calculated by [18]:

$$A_{geo.} = 10 \times \ log\ (\frac{d_t + L + \theta}{d_r})^2 (dB) \tag{7}$$

Where,d_r is the receiver diameter, d_t is the transmitter diameter (both in millimeters), and θ is the divergence angle in mm.rad/km.

Therefore, the received optical power at photo-detector is given by[18]:

$$P_r = P_t \times E_t \times E_r \times 10^{\frac{-A_{FSO}}{10}} \quad (mWatt) \tag{8}$$

Where,P_r is the transmitted power,P_t is the transmitted power, E_t is the transmitter optical efficiency, andE_r is the receiver optical efficiency

Also, there are two kinds of noise sources presented in FSO links which are external noise (ambient noise) and internal noise (includes dark current and thermal noises). Link noise degrades the received electrical SNR of FSO link which can be calculated as [19]:

$$SNR_{FSO} = \frac{(\eta P_r)^2}{2eB(\eta P_r + I_D) + 2eB\eta P_g + 4KTBF_n/R_L} \tag{9}$$

Where, η is the photo-detector's responsibility in A/W, e is the electron charge, I_D is the dark current, P_g is average background power, K Boltzmann constant, T is absolute temperature, R_L is the load resistor, F_n is noise figure and B is electrical bandwidth. The first, second and third terms in the denominator represent shot, background and thermal noises, respectively. Furthermore, M-PPM modulation format is used in simulated FSO link to enhance receiver sensitivity, especially at high ambient noise.

Furthermore, the desired BER of the FSO link can be obtained by adapting the modulation order M of the scheme as [21]:

$$BER_{FSO} = \frac{1}{2} erfc(\frac{1}{2\sqrt{2}}\sqrt{SNR_{FSO}\frac{M}{2}\log_2 M}) \tag{10}$$

3.2 mmW communication channel

The major impairments of mmW propagation in free space are path loss and rain attenuation. Also, like FSO, mmW link performance depends on the selected carrier frequency, modulation formant and transmitted power level.Path loss occurs due to the divergence in transmitted beam through its travel in free space. It is proportional to the square of distance between transmitter and receiver as [21]:

$$A_{PL} = 10 \times \log_{10}\left(\frac{4\pi\, L}{\lambda_m}\right)^2 \text{ (dB)} \tag{11}$$

Where,L is the distance between transmit and receive antennas, λ_m is the operating wavelength.Also, rain attenuation occurs as a result of the absorption and scattering of electromagnetic waves by rain particles. It depends on carrier frequency, temperature, rain droplet size, and rainfall rate. In general, there are two types of rain attenuation models: empirical and theoretical models. The most utilized empirical model is ITU-R which gives the calculations of rain attenuation by:

$$l_{Rain} = a \times R^b \times L \qquad \text{(dB)} \tag{12}$$

Where,a and b are the frequency dependent coefficients, and R is the rainfall rate (mm/hr).The received electrical SNR of mmW link can be defined as [21]:

$$SNR_{mmW} = pg/\sigma^2 \text{(dB)} \tag{13}$$

Where,p denote the transmitted power, g is the effective gain which can be modeled as [21]:

$$g = G_t \times G_r - A_{PL} - o_{ox.} \times L - l_{Rain} \text{(dB)} \tag{14}$$

Where, G_t and G_r denote the transmitting and receiving antenna gains, respectively, and $o_{ox.}$ is the attenuations caused by oxygen absorption (dB/km). σ^2 is the RF noise variance and is given by [21]:

$$\sigma^2 = B_m N_0 + N_F(\text{dB}) \qquad (15)$$

Where, B_m, N_0 and N_F denote RF bandwidth, noise power spectral density (in dBm/MHz) and noise figure of the receiver, respectively. Finally, the desired BER can be obtained by adapting the modulation order of M-QAM as [21]:

$$BER_{mmW} = \frac{4}{\log_2 M}(1 - \frac{1}{\sqrt{M}})Q(\sqrt{\frac{3\log_2 M}{M-1}}\sqrt{\frac{E_b}{N_0}} \qquad (16)$$

Moreover, a homogeneous foggy and rainy weather is assumed over the entire network with equal joint visibility-rainfall rate value.

4. Hybrid FSO/mmWfronthaul network in C-RAN

Hybrid FSO/mmW systems presents a promising solution to provide wireless fronthauling services for the traffic of RRHs on C-RAN architecture. The idea behind a combination between FSO and mmW is the complementary behavior of each technology during different weather conditions. As mentioned before, rain is the dominant cause for attenuation in mmW link, whereas fog is the most important cause for attenuation in FSO link. Recently, mmW became a feasible solution in the hybrid FSO/RF systems; due to the mmW technology can provide high data rates similar to FSO (multi Gbps). In addition, the mmW (70-80 GHz) bands are particularly attractive for long range communications because these bands have a very low O_2 and H_2O atmospheric absorption.

Therefore, when the FSO link fails the mmW can provide nearly the same throughput requirements in data transmission. The switching between the two links is depending on variations in the channel conditions as shown in Fig. 2. The flowchart for real time switching operation in hybrid FSO/mmWfronthaul network is indicated in Fig. 3. Initially, depending on the geographical service area, FSO link is selected to be the primary link in coastal cities whose weather is rainy. When the bit error rate on the FSO link exceeds the threshold value ($BER_{FSO} > 10^{-12}$)which is CPRI constraint, the hybrid system switches to the mmW link that is considered to be the secondary one to maintain the availability of the fronthaul network. In contrast, mmW link is considered to be the primary one in Agricultural lands whose weather is mainly foggy. When the bit error rate on the mmW link exceeds the threshold value ($BER_{mmW} > 10^{-12}$), thehybrid system switches to the FSO link that is considered to be the secondary one to maintain the availability of the fronthaul network.

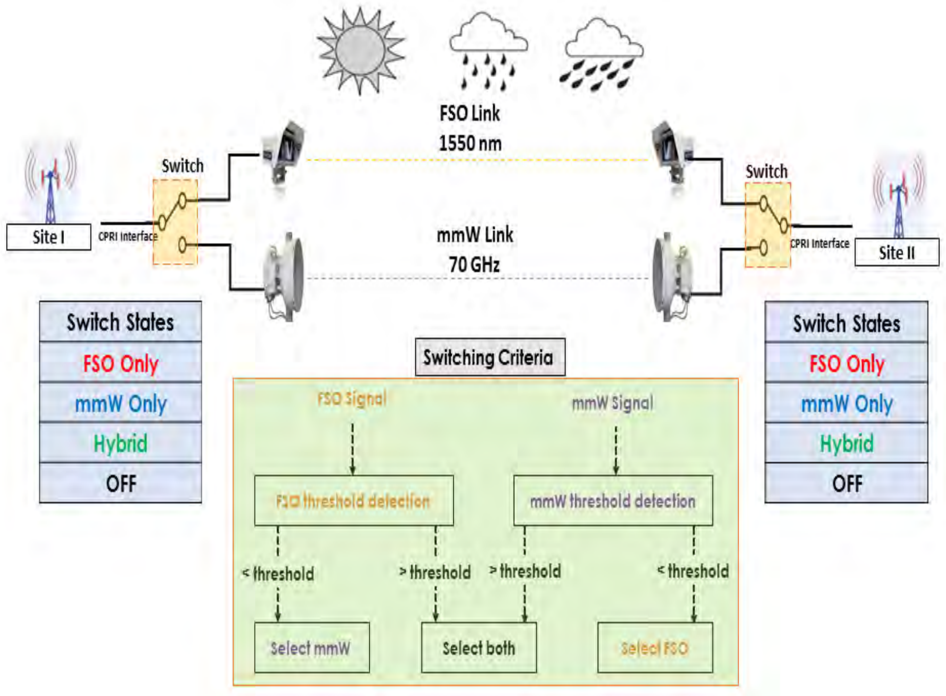

Fig. 2. The switching criteria between FSO and mmW links [6].

5. Simulation and numerical results

In this section, FSO, mmW and hybrid FSO/mmWfronthaul networks are numerically evaluated to indicate the superior performance of each system at different foggy and rainy weather conditions based on network availability. Since fog and rain are the dominant causes for attenuation in FSO and mmW links, respectively, each system is evaluated at different visibility and rainfall values.

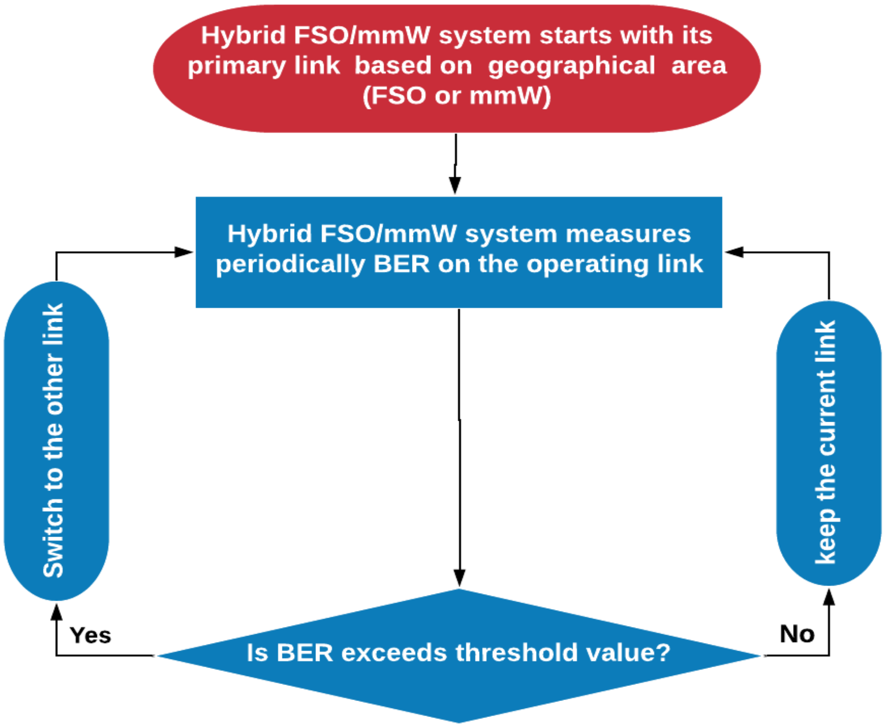

Fig. 3.Flow chart showing the real time switching operation in hybrid FSO/mmWfronthaul network.

As a study case, hybrid FSO/mmW system is proposed to be used as a fronthaul network in Egypt. Generally, the Egyptian weather in Giza has visibility values usually greater than 2 km, except it equals zero during 90 minutes only, but it becomes 1 km during 56.5 hr. [23]. Therefore, according to Kim model [11], fog attenuation on 1 km FSO link in the Egyptian weather varies between zero dB/km at visibility values $V \geq 2$ km and 20 dB/km at visibility value $V = 1$ km and reaches up to 350 dB/km at visibility values $V < 0.2$ km. Therefore, the effect of fog attenuation on FSO link on hybrid FSO/mmW system appears at visibility values less than or equal 1 km. Also, Egypt (especially in Alexandria) is awarded an average of 200 mm of rainfall per year, or 16.67 mm per month. The maximum rainfall rate occurs on January with around 75 mm/hr that may cause rain attenuation of 85 dB/km on 1 km mmW link [24].

The simulated network topology consists of 1RRH connected to BBU pool over distance ($L = 1$ km) point to point as shown in Fig. 3. The simulation parameters are given in table 1, where each FSO link uses 4-PPM modulation format with maximum bit rate 1.25Gbps, maximum transmitted power 19 dBm and maximum bit error rate 10^{-12} (CPRI constraint). From the table, the FSO receiver diameter is assumed to be $d_r = 0.2$ m and the maximum computed distance for FSO link in the simulated network topology is $L = 1$ km. The aperture averaging is then calculated as,$\varphi = [1 + 1.33 \times \left(\frac{2\pi}{\lambda} \times \frac{d_r^2}{L}\right)]^{-7/5} = 0.000513$.Clearly, using this value of aperture averaging, the attenuation variance caused by weak turbulences has small effect and can be neglected [15-16].Also, each mmW link uses BPSK modulation format with maximum bit rate 1.25Gbps, maximum transmitted power 14 dBm and maximum bit error rate 10^{-12}. These values are selected to be in the practical range [11-22].

Fig.4: Simulated network topology connected RRH with BBU pool.

Figures 5-6indicates the performance of FSO, mmW and hybrid FSO/mmWfronthaul systems at different foggy and rainy weather conditions in terms of network availability. Obviously, at clear weather, FSO, mmW and hybrid FSO/mmWsystemscan work with network availability reaches to 100%.

Table. 1. Simulation parameters [11-22]

FSO Link Parameters	Values
Signal wavelength (λ)	1550 nm
Divergence angle (θ)	2 mm.rad
Diameter of transmitter (d_t)	8 cm
Diameter of receiver (d_r)	20 cm
Efficiency of transmitter (E_t)	0.75

Efficiency of receiver (E_r)	0.75
Transmitted Power	19 dBm
background noise power	-52 dBm
bit rates	1.25Gbps
Modulation format	4-PPM
BER threshold (BER_{max})	
mmW Link Parameters	**Values**
Signal frequency (f)	72 GHz
elevation angle (ϑ)	0 degree
Polarization angle (α)	45 degree
Receiver noise figure (F)	7 dB
Transmitter gain (G_t)	41 dBi
Receive gain (G_r)	41 dBi
Transmitted Power	14 dBm
Noise power density (N_0)	-114 dBm/MHz
Discrete bit rates	1.25 Gbps
Modulation format	BPSK
BER threshold (BER_{max})	

Figure 5 shows the network availability of FSO, mmW and hybrid FSO/mmWfronthaul systems at different foggy weather conditions. Clearly, at haze and moderate foggy weather, especially at $V \geq 0.55$ km, network availability of FSO, mmW and hybrid FSO/mmWsystemsreach to 100%. However, at $V < 0.55$ km, the network availability of FSO system decreases gradually until it reaches to 0% at $V < 0.24$ km which is considered as heavy foggy weather. In contrast, mmW and hybrid FSO/mmW systems maintain their 100% network availability as fog has no effect on mmW links presented in mmW and hybrid FSO/mmW systems.

Figure 6 shows the network availability of FSO, mmW and hybrid FSO/mmWfronthaul systems at different rainy weather conditions. Clearly, at light rain, especially at $R \leq 2$ mm/hr, network availability mmW system reaches to 100%. However, at $R > 2$ mm/hr, the network availability of mmW system decreases gradually until it reaches to 0% at $R > 68$ mm/hr which is considered as heavy rain. In contrast, FSO and hybrid FSO/mmW systems maintain their 100% network availability until $R > 86$mm/hr, and then network availability decreases gradually until it reaches to 19% at $R > 150$mm/hr due to rain has slightly effect on the FSO links presented in FSO and hybrid FSO/mmWfronthaul systems.

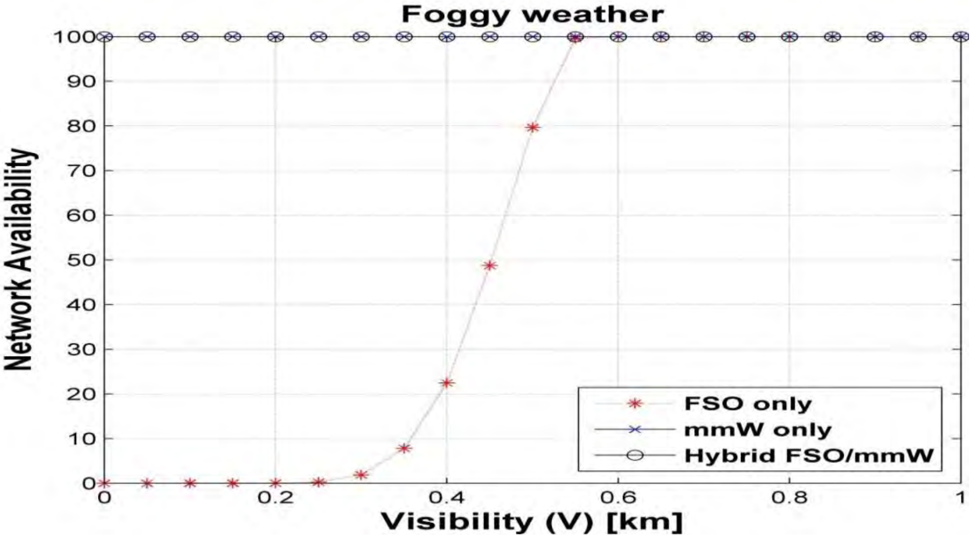

Fig. 5.Network availability versus visibility *(V)* in km for FSO, mmW and hybrid FSO/mmWfronthaul systems.

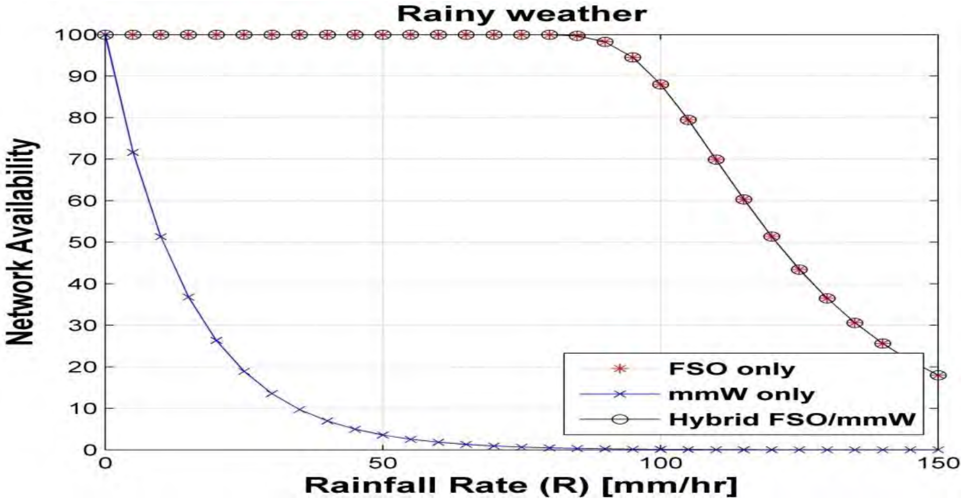

Fig. 6.Network availability versus rainfall rate *(R)* in mm/hr for FSO, mmW and hybrid FSO/mmWfronthaul systems.

As a summary, at clear weather, FSO, mmW and hybrid FSO/mmW systems can work with network availability reaches to 100%. At heavy foggy weather ($V < 0.24$), mmW link in the hybrid system will be the preferred one. In contrast, at heavy rainy weather ($R > 68$), the hybrid system will select the FSO link.

6. Conclusion

Hybrid FSO/mmW network is considered to be apromising solution to support 5G fronthauling services in C-RAN architecture. The performance of hybrid FSO/mmW link relies on channel models of both FSO and mmW which experience different attenuations atthe same weather conditions. Generally, FSO link ismainly affected by fog attenuation, while rain attenuation is the dominant in mmW link. By exploiting thecomplementary behavior of FSO and mmW links at various weather conditions, hybrid FSO/mmW fronthaul network achieves better performance than that FSO and mmW ones.

7. Acknowledgement

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الملخص باللغة العربية

مع التطورات المستمرة الذي يشهدها عالم تكنولوجيا المعلومات, هناك أبتكار جديد يدعى شبكة الوصول للراديو المركزية. تطوير هذه الشبكة تم من أجل تلبية الأحتياجات المتزايدة للحصول على البيانات بسرعة و بسعة أكبر في الجيل الخامس. بالرغم من هذا التطور, ما زال هناك فجوة بين متطلبات الزيادة المستمرة في سعة البيانات و النقص الشديد في الترداداتت المتوافرة مما يدفعنا للتفكير في تطوير طرق نقل البيانات اللاسلكية الحالية. يتم الربط بين ابراج الراديو و وحدة معالجة الأشارات في شبكة الوصول للراديو المركزية عن طريق شبكة نقل بيانات مطورة. تقوم هذه الشبكة بنقل كمية كبيرة من اشارات المستخدمين من/إلى ابراج الراديو إلى/من وحدة معالجة الأشارات بسرعة كبيرة جداً. نقترح في هذا البحث الدمج بين نظم الأتصالات البصرية اللاسلكية و الموجات المليمترية كحل واعد من أجل استخدامه كشبكة لنقل البيانات في شبكة الوصول للراديو المركزية في الجيل الخامس و ذلك لأن هذا النظام المدمج سيحسن من توافر شبكة نقل البيانات بأستمرار في الظروف الجوية المختلفة كما يمكنه توفير السرعة و السعة الكبيرة المطلوبة بأستمرار مع ان أجل اتمام هذه العملية. بالأضافة إلى ذلك يقترح هذا البحث طريقة للتبديل بين نظم الأتصالات البصرية اللاسلكية و الوجات المليمترية و اختيار التكنولوجيا المناسبة لنقل البيانات عليها وفقاً لطبيعة الظروف الجوية. ايضاً تم دراسة اداء هذا النظام المدمج في الظروف الجوية المختلفة و تم مقارنته بأداء أنظمة لأخرى لأختيار الأفضل. النتائج الرقمية وضحت ان هناك تحسينات في توافر شبكة نقل البيانات نتيجة الدمج بين نظم الأتصالات البصرية اللاسلكية و الوجات المليمترية في شبكة الوصول للراديو المركزية خاصة في حالات وجود شابورة كثيفة تعيق الرؤية بشكل كبير أو هطول أمطار بشكل كبير.