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6G networks: insights and reliability analysis

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ABSTRACT

As we are living in a fast-moving dynamic world. Emerging technologies such as artificial intelligence (AI), internet of things (IoT), virtual reality (VR), augmented reality (AR), fourth industrial revolution (Industry 4.0), metaverse, and edge computing are expected to play an essential role in our daily life. These technologies require high-speed, sustainable, and reliable communications networks which are expected by sixth generation (6G) wireless communications networks. 6G will be the backbone for these emerging technologies as well as for the technology-driven digital infrastructure. Governments as well as research and development (R&D) of the technology companies are gearing up to conduct a regulatory framework to standardize 6G networks; studying and conducting experimental setups to examine and evaluate the deployment of 6G networks; both in which they will have opportunities and challenges. This paper provides insights and guidelines for 6G networks in terms of standards, implementations, applications, and research trends. In addition, it provides reliability analysis for terrestrial 6G networks. A carrier class availability could be achieved over a maximum of 4 km link distance. These insights and availability figures may be used as a useful tool for researchers and industry stakeholders for the deployment and rollout of the next generation 6G wireless communications networks.

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1. INTRODUCTION

The sixth generation (6G) technology vision is to be a merged structure of a tremendous number of smart devices into a single global connectivity that provides interactions between humans and devices. In the present work, we touch briefly on what would 6G be like? Identify the main key players that are involved in the development of 6G and 6G standards. Next generation 6G wireless communications networks can only be commercialized if the 6G standardizes and the operation of integrated terrestrial networks (TN) and non-terrestrial networks (NTN) vision is clear. 6G is still in the research and development (R&D) phase. The goal of 6G is to have an ecosystem where all devices can thereby harmoniously integrate with humans to deliver immersive user experience to the consumers. To examine the reliability of 6G networks, availability assessments are needed. In this paper, link availability for terrestrial 6G networks has been investigated using the availability prediction model for a hybrid free space optics (FSO)/terahertz (THz) link. It provides estimation of 6G terrestrial link availability performance for the deployment of 6G networks with respect to link distance. This paper is organized as follows: section 2 discussed the 6G technology race and current status. Section 3 provides insights into standards and challenges of 6G technology. Section 4 explores the 6G potential applications and brief discussion on research trends. Section 5 illustrates the reliability prediction method of hybrid FSO/RF networks that will be used for 6G networks followed by results and discussions in section 6. Section 7 is conclusion.

2. 6G: RACE AND CURRENT STATUS
2.1. Race towards sustainable 6G networks
Unlike previous mobile generations where only the west was dominant; the race in 5G and beyond mobile networks currently is heating up between east and west. Currently China leads in 5G and has even more market share in the 5G global market. The question is who is going to take the lead in the 6G next generation of wireless network communications. Although 6G wireless networks are expected to rollout in 2029 and commercially launch in 2030 [1]. Many competitors are taking part in the 6G next generation mobile systems' global competition. The list could be very long. In this paper, some of these major research groups are highlighted to give an idea of the 6G race roadmap landscape. The 6G Flagship research program at University of Oulu was the first one to participate in the 6G race in May 2018 in Finland [1]. They conduct about ten 6G projects in which they establish a research vision and observe recent development in 6G. One of the projects is Hexa-X led by Nokia and in collaboration with Ericsson and TIM. Their projects involve the 6G standards framework, technical applications and future technology trends. Moreover, they have been conducting 6G wireless summit events to promote 6G research visions. They published a series of 6G white papers written by an international expert group in next-generation wireless communications systems. In 2019 at one of the 6G global summits; the Chinese technology giant (Huawei) jumped into the 6G race and proposed its vision to launch more than ten thousand satellites to provide global coverage of 6G networks [2]. Later in June 2020, they had an air-space-ground partnership agreement with China Unicom and Galaxy Aerospace to develop the 6G networks. On November 7, 2020, China marked a breakthrough in the 6G race by launching the world's first 6G satellite from Taiyuan Satellite Centre into space according to the state-affiliated daily Global Times and other international media around the world. The main objective of this experiment was to evaluate and examine the performance of very high frequencies of terahertz which are expected to be the frequency bands of 6G communications networks. In June 2021, LG Electronics was stepped up by its Application Working Group of the Next G Alliance to advance the 6G technology roadmap in North America [3]. The research activities are conducted in the Research and Standards Lab in LG USA. On 6 January 2022, Chinese lab namely the purple mountain (government-backed laboratories) in collaboration with telecoms giant China mobile and Fudan University has made a tremendous breakthrough in the race of 6G according to the South China morning post. They used a self-developed 360-430 GHz wireless communication system. They achieved a speed of up to 206.25 Gbps real time terahertz transmission. In September 2022, LG Electronics in collaboration with Fraunhofer Heinrich Hertz Institute (HHI) in Berlin successfully managed to establish a 320-meter outdoor transmission link using 155-175 GHz frequency range which heats up the global 6G race [4].

2.2. 6G current status
As we can see, there are a wide range of research groups from all over the world involved in the 6G global race. They are from different Tech industries and academia such as research institutes, universities, and telecoms companies. All in which engaging and cooperating in extensive research and experiments to possess the 6G global leadership. They are extensively working to obtain all kinds of innovations and patents in 6G technology. In February 2023, the Korean Ministry of science and ICT officially announced that South Korea will be the first country in the world to launch a 6G network in 2028 using state of the art technology. The government of South Korea will support its local companies to develop such hardware and softwares that is needed to provide sustainable 6G networks. Such a move will let South Korea win the race on launching the world's first commercialization of 6G next generation wireless communications networks. Will other countries make such a move to remain in the 6G global race?

3. 6G STANDARDS AND CHALLENGES
Formulating the 6G standard will be a key milestone in the development of the next generation wireless communications systems. It will accelerate R&D activities as well as the implementation and deployment of 6G networks. 6G is expected to start formulating its global standards in 2025. As a matter of fact, 6G standards may face two main challenges before the commercialization phase. The first challenge is setting up the 6G standards policies and recommendations in which it should be agreed and recognized by global regulatory bodies. Despite the geopolitical dispute, the 6G industry needs being standardized under the umbrella of 6G global connectivity for a better future. Accepted regulatory frameworks are an important part to achieve sustainable and convenient global 6G networks. The second challenge is the implementation and deployment of 6G networks. Unlike 5G, 6G is expected to provide global connectivity covering earth and

outer space thereby requiring integrated networks. Such systems required massive technical efforts from transdisciplinary technology industries to fulfil the potential of 6G technologies. To have wider view on these two challenges: a brief elaboration in the following sections.

3.1. 6G standards policies and recommendations

As of now, there is no spectrum officially allocated yet to 6G technology. First Standardization efforts toward the 6G sub-terahertz band were introduced [5]. With the approved amendment of the IEEE802.15.3d to 802.15.3, this could be considered a first step into the development of 6G standards. 100 GHz–3 THz frequency bands are also promising bands for the 6G technology [6], [7]. Such high frequency bands yield high data rates in the order of terabit per second (Tb/s) [8]. Another important aspect that must be addressed carefully during the development of the 6G standards is the impact of THz radiation on the biological effects on humans and animals. Safety measures must be carefully implemented in the case that THz radiation waves are found to be harmful for the human bodies [6]. Although 6G is still in the R&D phase, the potential of 6G technologies is something that governments and technology sectors could not ignore. Governments along with telecom service providers, technology experts and academia in collaboration with international standards organizations are the key players in providing sedate standards; once the 6G technology is backed by scalable and adaptable standards policies and recommendations; it could be ready for commercialization to deliver the optimal user experience to the 6G technology consumers. Therefore, the role of these key players is very important at this stage. Upon agreeing on policies and finalizing the 6G standards; recommendations may be provided to the international level by the technical professional organizations and standard agencies such as IEEE Standards Association (IEEE SA), European Telecommunication Standards (ETSI), and International Telecommunication Union (ITU).

3.2. Implementation and deployment of 6G networks

Unlike previous mobile generations, 6G network architecture will be different. Most 5G networks connectivity are terrestrial where all base stations are installed on earth, whereas 6G will be more likely terrestrial and NTNs. There will be TNs on earth that integrate with non-terrestrial in space to deliver intelligent and sustainable worldwide connectivity [9], [10]. Thus, many technical challenges in all aspects are expected to arise during the development of 6G technology. Therefore, 6G networks will require extensive research, surveys, and experiments to address all these technical issues and limitations that may occur during the development of 6G networks. For example, at terrestrial level. 6G required high capacity compared to 5G. In such a scenario, one of the possible ways to fulfill the increment of 6G capacity is to reduce the cell size to an attocell network instead of existing femtocells used by 5G [11], [12]. Thereby, the cell size will be about a dozen square meters. In such a cell size, optical wireless communications like visible light communications (VLC) could be used instead of RF for indoor applications [13]. For outdoor or longer distances free space optical (FSO) communication could be complementary to RF due to its advantages in providing high bandwidth, very secure and license free, but it has limitations due to weather effects. Thus, one of the main emerging technologies that is expected to play an important role in the implementation of 6G networks are hybrid FSO/THz systems. These systems are expected to be used in 6G connectivity for backhauling [14]-[18]. Hybrid FSO/THz systems are highly reliable with high-speed that can satisfy the bandwidth of 6G due to their distinct characteristics in providing a trade-off between FSO speed and reliability of THz. Figure 1 illustrates a hybrid FSO/THz network that may be used for 6G backhauling connectivity.

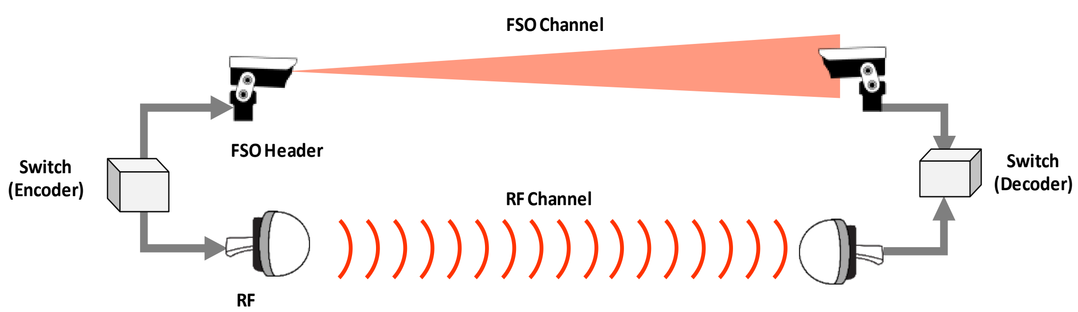

Figure 1. Hybrid FSO/THz networks are promising for 6G backhauling connectivity [14]

Moreover, in each aspect of the developments and deployment of 6G, there will be a technical challenge which requires extensive efforts to overcome all these technical issues. Based on the current development and requirements of 6G, we may predict some of the 6G specifications. Table 1 shows the 6G promising specifications.

Table 1. 6G promising specifications

Items	Specifications
Frequency band	Electronics: 100 GHz > 10 THz
	Photonic spec: optical wireless (FSO/VLC)
Data rate/speed	<1 Tb/s
Latency	Mostly does not exist
Sustainability	Carrier class availability
Network architecture	Integrated networks: TN/NTN
Connectivity	Intelligent, smart sensing technology

4. 6G APPLICATIONS AND RESEARCH TRENDS

6G next generation wireless communications networks will integrate global sustainable connection of intelligence systems with everything including smart sensing. Thereby, there will be tremendous applications of 6G technology that are connected using 6G networks starting from billions of devices on earth to thousands of satellites in outer space. A brief discussion on 6G applications followed by research trends in the following sections.

4.1. 6G applications

Some of the major applications that will be used for 6G technology are [9]:

- Extended reality (XR): consists mainly of augmented reality (AR), virtual reality (VR), and mixed reality (MR) which are used for remote activities. 6G technology will deliver a revolutionary user experience with a wide range of 360° views and very high resolutions rate. XR technology will use human-machine interfaces. It will integrate with glass-free 3D and holographic displays. Online meetings or conferences will be replaced by holographic meetings/communications. Our physical world will transform into a digital world.
- Sensing: a new function that integrated with 6G communication systems to provide sensing that can measure and analyze wireless signals. This capability may turn 6G networks into sensors. Localization, gesture, activity recognition, imaging and mapping are among the new sensing applications. Network sensing enables us to determine our location, explore things around us and integrate with artificial intelligence (AI), machine learning (ML), and digital twins' technologies to collect, analyze, and deliver real-time data with seamless services to the consumer. Sensing capability will deliver enhanced solutions in many areas such as smart factories and homes, intelligent transportation, air quality measurements, and public safety.
- Telemedicine: is expected to play a vital role in the development of the healthcare system during the 6G era. Transformation of the health care systems into digital wearables devices, telesurgery can be performed using implanted sensors.
- Emerging technologies: due to the 6G stringent requirements including a high-speed, sustainable, and high-resolution rate; 6G next generations networks are expected to continue what has been formulated and established by 5G but in large-scale 6G networks deployments. Thereby, emerging technologies like AI, internet of things (IoT), smart cities, and manufacturing (Industry 4.0) are expected to be more intelligent and efficient in the 6G era compared to 5G [19]. Moreover, due to extensive smart sensing nodes deployment, 6G more likely plays an important role in renewable energy and smart grids resulting in more energy efficiency. Furthermore, Blockchain technology may be used in 5G and beyond networks due to its resource sharing function and mobility [20]. In such applications, security and privacy are two main parameters that should be addressed mainly on the 6G network edge [21].

4.2. 6G research trends

6G technology is 5 years away from being commercialized. Till that time, there is massive work that needs to be done to reach the universal sustainable wireless connectivity that transforms human life from physical into a digital world. 6G research trends could be identified by ideas of the 6G challenges and potential applications that were mentioned in the previous sections. 6G needs engineering and computer science skills, academics, law makers, marketing specialists, telecom professionals, technology, and space experts and more efforts to really make it doable. As the research of 6G has already started and still needs huge efforts; Leading universities and research institutes are expected to start conducting research work and take part to advise the government to formulate national policies and standards for 6G. Meanwhile, Marketing specialists of telecom industries can also promote commercial and research opportunities for the industry of AI for next-generation technologies. There are plenty of research directions for 6G technology; and the list of 6G research trends is endless and hard to be comprehensive. Brief discussion on some of the 6G technical research trends as follow:

- 6G systems: such as transmit power, antennas, implanted sensors, and all aspects related to the equipment parameters including materials that may be used to achieve THz/Tbps systems. For example, novel antenna designs that may enhance the performance for 6G wireless systems [22]-[24] or using MIMO technology for 6G networks [25].
- 6G networks architecture: the 6G networks will most likely be an integration of TN and NTN as illustrated in Figure 2. At the terrestrial level: evaluations and analysis of the impact of different weather phenomenon such as rain, fog, and haze on the performance of THz waves as well as optical wireless link need to be studied. Careful consideration with respect to the geographical locations in link design for THz and optical waves. In the case of using hybrid optical/THz systems, a proper integration of THz with optical waves could be another research direction. At outer space: satellite communications will get more research attention as it will help 6G to provide global connectivity covering all earth. Another research aspect is software define network (SDN) that can be used for network configurations and automations. More research on how the programmable end–to-end SDN based control planes can achieve seamless convergence with careful excursion. Recently, deployment of a high-altitude platform station (HAPS) in the stratosphere at an altitude of 20-50 km showed attention for backhauling aerial base stations in 6G wireless systems [26].

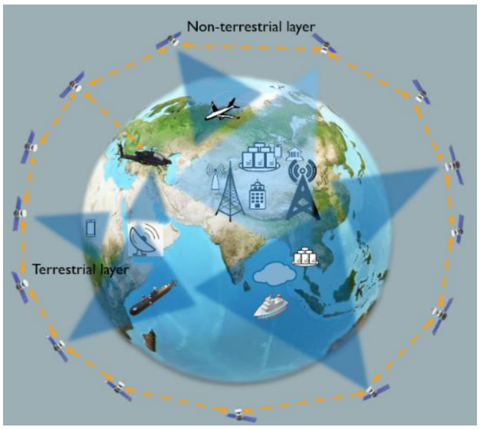

Figure 2. 6G networks architecture: integration of TN and NTN

5. RELIABILITY PREDICTION METHOD FOR 6G TERRESTRIAL NETWORKS

One of the major aspects that would be investigated and studied is how reliable 6G performance will be. As 6G networks will be integration of TN and NTN; Reliability performance should be studied in the two different environments in earth and outer space. For terrestrial links, reliability performance will differ from one area to another depending on weather phenomena. Availability performance of hybrid FSO/THz systems could be an important part of the overall reliability performance for terrestrial 6G networks. In such systems availability prediction can be expressed as (1) [14]:

$$A_{Hybrid} = (1 - (P_{out,FSO}).(P_{out,RF})) \times 100\% \quad (1)$$

where: A_{Hybrid} : hybrid FSO/RF link availability

$P_{out,FSO}$: outage probability of FSO link in decimal

$P_{out,RF}$: outage probability of RF link in decimal

$P_{out,FSO}$ can be determined as (2):

$$P_{out,FSO}(\%) = a_0\, exp(\, b_0.\, |Fm_{FSO}|) \quad (2)$$

where a_0 and b_0 are constants coefficients; Fm_{FSO} is FSO fade margin (dB).

$$a_0 = \begin{cases} 4.409 & d \leq 1\ km \\ 165.4(d)^{-6.599} + 7.85 & 1\ km < d \leq 5\ km \end{cases} \quad (3)$$

$$b_0 = -0.3147(d)^{-0.9964} \quad (4)$$

Whereas $P_{out,RF}$ can be determined as (5):

$$P_{out,RF}(\%) = a\, exp(\, b. |Fm_{RF}|) \quad (5)$$

where *a* and *b* are constants coefficients; Fm_{RF} is RF fade margin (dB).

$$a = \begin{cases} 0.5314\, f^{\,0.4326} & d \leq 1\ km \\ 3.584\, f^{-0.09082} & 1\ km < d \leq 5\ km \end{cases} \quad (6)$$

$$b = \begin{cases} -306.6\, f^{-2.202} - 0.1804 & d \leq 1\ km \\ -168.5\, f^{-2.073} - 0.1017 & 1\ km < d \leq 2\ km \\ -138.1\, f^{-2.076} - 0.07912 & 2\ km < d \leq 3\ km \\ -118.7\, f^{-2.077} - 0.06521 & 3\ km < d \leq 4\ km \\ -105.9\, f^{-2.08} - 0.05571 & 4\ km < d \leq 5\ km \end{cases} \quad (7)$$

6. RESULTS AND DISCUSSION

In this section availability of a terrestrial hybrid FSO/RF link is analyzed using the availability prediction model [14], in (1) to (7). The model is selected as it can provide prediction for up to 0.1 THz radio link under tropical climate where rain is the dominant factor. The model also considered other weather phenomena such as haze and smoke which could have the same impact as fog in temperate regions. Thus, these availability figures could be matched to tropical areas and areas where rain is most weather phenomena. In addition, it could provide possible availability figures of the deployment of the hybrid FSO/THz links for 6G TNs in temperate regions. The analysis is up to 5 km link distance for 100 GHz radio frequency. Two cases were considered. In the first case a 15 and 30 dB fade margin for FSO and 100 GHz respectively were considered as illustrated in Figure 3. FSO link can only achieve 99.999% (five nines/carrier class) availability over 500-meter link distance, whereas 99.99% (four nines/enterprise class) availability can be obtained over 700-meter FSO link. When the FSO link has a complementary link of 100 GHz link to form hybrid FSO/100 GHz link that will boost the reliability of the 6G terrestrial link over longer distances. The hybrid FSO/100 GHz can achieve carrier class availability over a 2.9 km link distance. Can achieve enterprise class availability over a four km link distance as depicted in Figure 3.

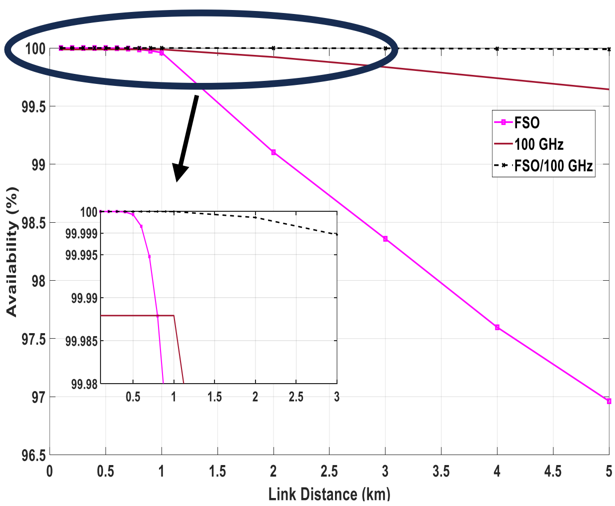

Figure 3. Availability prediction of terrestrial 6G networks: enterprise and carrier class. For a fade margin of 15 and 30 dB for FSO and 100 GHz respectively

Thus, to increase the link distance and maintain a high-rate reliable link. One of the possible options is to increase the fade margin for FSO and RF links as shown in Figure 4. The fade margin for the second case was increased to become 30 dB and 50 dB for FSO and 100 GHz respectively. In such a case, FSO link can achieve carrier class as well enterprise class availability over 1 and 1.2 km link distances respectively. Whereas hybrid FSO/100 GHz link can achieve five-nines availability over four km link distance. Moreover, enterprise availability can be achieved over a five km link distance. That indicates an increment of fade margin for FSO, and THz link will increase the link distances by a few kilometers. The 6G networks, both TN and NTN are expected to be extremely reliable as they are used for mostly stationary applications. Thus, for 6G backhauling connectivity where hybrid FSO/THz links may be used, a fade margin of 15 and 30 dB for FSO and 100 GHz links respectively are required to achieve carrier class availability of 6G TNs over a maximum of 2 km link distance. Furthermore, to maintain this high availability, fade margins of 30 and 50 dB for FSO and 100 GHz respectively are recommended for a maximum four km link distance. Such availability figures will provide a knowledge of the required parameters of the 6G link for each application/user case including backhauling connectivity. Availability is one of the essential requirements and key performance indicators (KPI) for 6G networks. Thus, most of the applications enabled by the next 6G networks will require a combination of ultra-low latency with extremely high availability, reliability, and security. Desired availability of 6G networks will be based on the user cases. For example, autonomous vehicle control desired 99.999% availability compared to 99.9% required by a massive number of devices. As a result, autonomous vehicle control may need hybrid FSO/THz link with 15 and 30 dB fade margin for FSO and RF respectively to achieve 99.999% over a maximum link of 2.9 km.

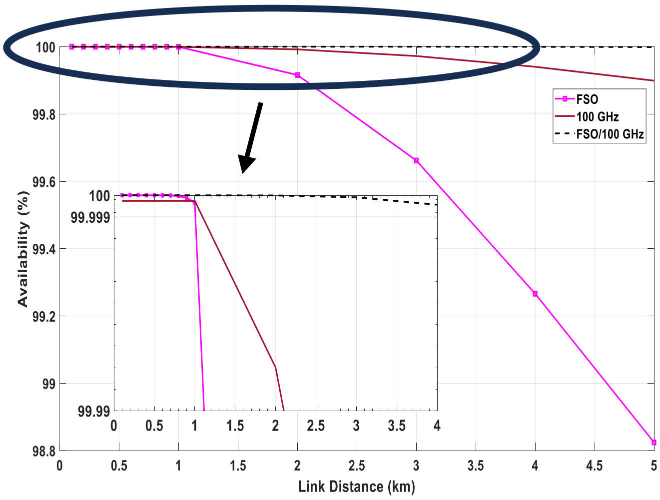

Figure 4. Availability prediction of terrestrial 6G networks: enterprise and carrier class. For a fade margin of 30 and 50 dB for FSO and 100 GHz respectively

The system's fade margin for both FSO and THz can play an important role in the deployment of terrestrial 6G networks. Availability is directly proportional to the link margin for both FSO and THz links as depicted in Figures 5 and 6. Over a one km link distance, a fade margin of 20 dB and 35 dB can achieve 99.99% availability of FSO and 100 GHz links respectively. Increasing this fade margin to 30 and 45 dB will result in 5 nines availability for FSO and 100 GHz respectively as shown in Figure 5. For the same link distance, a hybrid FSO/100 GHz link can seamlessly obtain carrier class availability for a 15 dB fade margin for both FSO and 100 GHz links. Factory automations operate over a one km link distance, and they desired 99.99% availability. Thus, they required 20 dB and 35 dB fade margin for FSO and RF links respectively.

Moreover, increasing the link distance will require an additional fade margin to maintain enterprise or carrier class availability. For instance, over a two km link distance, a fade margin of 45 dB and 50 dB can achieve 99.99% availability of FSO and 100 GHz links respectively. Increasing this fade margin to 60 dB will result in 5 nines availability for FSO link only as shown in Figure 6. For the same link distance, a hybrid FSO/100 GHz link can seamlessly obtain carrier class availability for a 20 dB fade margin for both FSO and 100 GHz links.

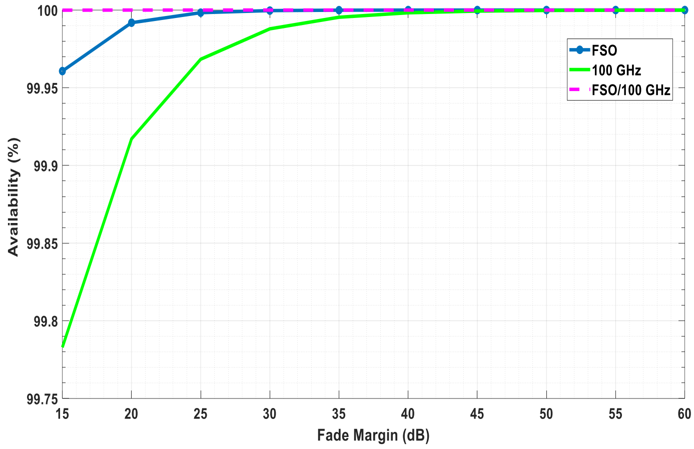

Figure 5. Availability prediction of terrestrial 6G networks as a function of fade margin over 1 km link distance

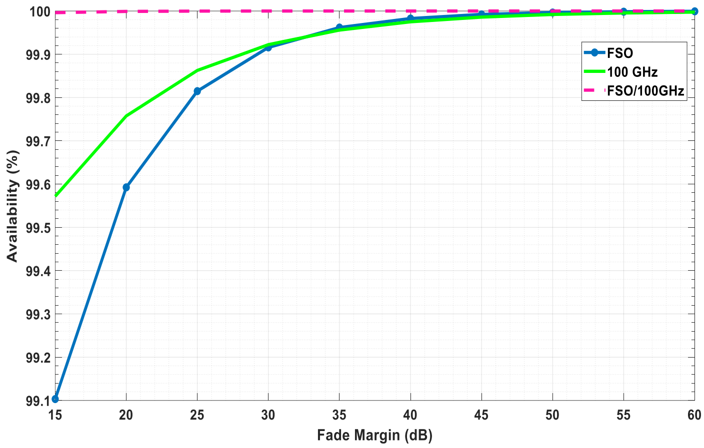

Figure 6. Availability prediction of terrestrial 6G networks as a function of fade margin over 2 km link distance

7. CONCLUSION

The 6G race is heating up, although there are challenges but 6G technology opens doors of opportunity in topics yet largely unexplored. This paper has provided insights into the developments of 6G networks with an emphasis on existing and potential 6G standards, applications, and research trends. Moreover, recommendations for the availability of 6G TNs have been analyzed. Hybrid FSO/THz links can boost the reliability of 6G networks. Carrier class availability can be achieved over a maximum 4 km link distance for a fad margin of 30 and 50 dB for FSO and THz links respectively. Further studies and analysis on reliability for the 6G NTNs are needed to provide an overall view on the performance of the integrated 6G networks. The 6G networks will enable humans and machines to interact with their environment, in real time, while on the move and within a certain spatial communication range. Availability figures that may be used for different applications of the next generation 6G networks are provided with respect to a link distance.

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