High-Altitude Configuration of Non-Terrestrial Telecommunication Network using Optical Wireless Technologies

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Abstract: Non-terrestrial communication technologies will become a key component for the development of future 6th generation (6G) networks. Potentials, implementation prospects, problems and solutions for non-terrestrial telecommunications remain open areas for future research. The article discusses the use of millimeter and optical wavelengths in various configurations of multilevel space communications using LEO satellites, stratospheric platforms and unmanned repeaters. The comparison of the capacity of the Shannon channel for various multi-level scenarios of the satellite communication line is carried out. The directions of research are analyzed to ensure the continuity of communication, adaptation to weather conditions, and achieving a throughput of up to 100 Gbit/s.

Key words: non-terrestrial network (NTN); 6G; satellite connection; unmanned aerial vehicles (UAVs); stratospheric platforms (HAPs), space network configurations; millimeter waves; optical wireless systems; communication efficiency assessment

1. Introduction

The proliferation of smart devices and wireless applications with demand for higher transmission quality is driving the need for increased RF bandwidth. So far, the solution for the deployment of next-generation networks in cities is the densification of cellular nodes with high-bandwidth fiber-optic backhaul connections. However, deploying networks in sparsely populated areas and over long distances with high bandwidth remains a challenge. Today, the most productive in terms of bandwidth are fiber-optic systems, for which the maximum experimental speeds are hundreds of Tbit/s, but still do not allow the quality of 5G and subsequent generations to be realized on a global scale. A possible solution to this problem is a multi-level communication system that integrates terrestrial and non-terrestrial telecommunication systems. Due to technological progress in the field of satellite technologies, projects of low-earth orbit systems (LEO) are being implemented at the moment. Amazon's Kuiper, SpaceX's Starlink and OneWeb are three of the major next-generation LEO constellations currently under development, all of which promise to provide high-speed, low-latency broadband connections around the world. The new LEO projects provide for the use of millimeter wave (MMD) and optical spectrum (OS) [1-5]. The ability to connect to a satellite network can be improved through the use of communication channels in MMD and OS between satellites. This will increase the capacity of telecommunication systems, as well as the ability to relay data from the Earth observation satellite to the ground via the GEO relay satellite, which provides real-time data flow and minimizes the number of ground stations required to provide services in the system. The use of OS and MMD in space has even greater potential compared to ground-based systems, since the absence of a physical medium for signal absorption will allow obtaining a high speed of information transfer. Currently, the main focus is on the use of laser communications to communicate between the Earth and Earth satellites. Fiber optic and optoelectronic technologies are also considered as an effective solution for the implementation of millimeter communication technologies, as well as for the formation of directional radiation by hybrid optoelectronic (photonic) methods in phased antenna arrays. Methods for converting the millimeter radio frequency range into the optical range is a promising way to increase the throughput of hybrid fiber-air terrestrial communication systems [6-8].

Therefore, research directions have emerged in the field of combining heterogeneous technologies, including terrestrial wireless, fiber-optic and non-terrestrial (satellite, stratospheric, unmanned) communication systems. Combining such technologies using the millimeter wave can provide high bandwidth and wide geographic coverage, despite very long transmission distances and strong attenuation at these frequencies. The researchers also realized that for the implementation of satellite Internet, it is necessary to create fully integrated non-terrestrial and terrestrial networks. Therefore, it will be advisable to analyze the possible architecture options for such physically multilevel telecommunication systems, to determine the technological and physical restrictions on the coverage area, bandwidth, other parameters and capabilities.

2. Multilevel communication system between ground and non-ground segments

The idea of creating multi-level communication systems between ground and non-ground segments appeared due to technical progress in the field of creating air and space miniature satellite platforms that can operate similarly to ground base stations. Non-terrestrial platforms include the following systems (Fig. 1).

Space communication satellites, according to orbit altitude, are divided into low-orbit LEO, medium-altitude (MEO) and geostationary (GEO).

Stratospheric platforms HAPs (High Altitude Platform), located at an altitude of 18-25 km (due to the peculiarity of the atmosphere at these altitudes, the temperature is almost constant and there are no winds). They can cover distances of hundreds of kilometers, operate for long periods of time, but they can also return to earth for reconfiguration. The propagation delay of 50-85 s is significantly lower compared to GEO (120 ms), MEO (15-85 ms) and even LEO (1.5-3

ms). Stratospheric platforms may contain Mobile Edge Cloud (MEC) features to offer terrestrial terminals additional computing and storage capabilities, thereby expanding coverage towards 3D.
Low-altitude platforms (LAPs) or unmanned aerial vehicles (UAV, English Unmanned Aerial LAP Vehicle, UAV), which also include tethered balloons. UAVs are predicted to be an important component for wireless deployment in the near future.
Optimizing the architecture of such a tiered system also facilitates the transition to Software Defined Networking (SDN), which, when combined with network partitioning, facilitates the deployment and management of Virtualization Network Functions (VNF) across multiple physical platforms.
Such a network architecture using software control can provide adaptation in the allocation of frequency resources, antenna power and directivity, fast response to traffic changes and load dynamics.

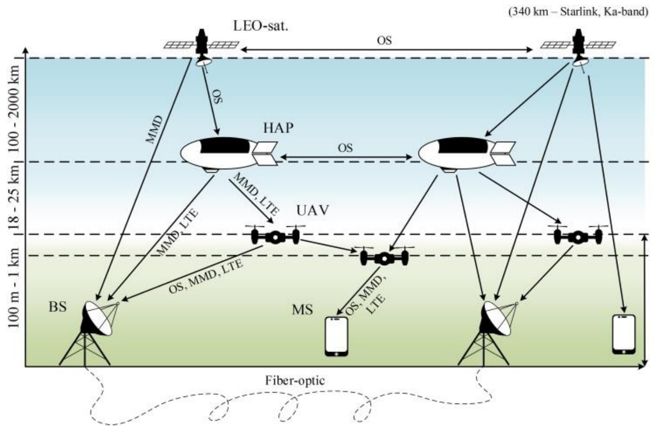

Figure 1. Multilevel space communications architecture using LEO satellites, stratospheric platforms and unmanned retranslators

3. Application of the optical and radio frequency spectrum in a multi-level network structure

The key solution for improving the performance of wireless telecommunication networks can be the use of MMD and OS, which allow organizing transmission channels with a width of several gigahertz, and the bandwidth that corresponds to the channel width. For 5G mobile systems, the solution to increasing capacity is to reduce cell size and increase base station density accordingly. The 60 GHz band, where strong atmospheric absorption is observed, is considered as an option for microcells, since natural absorption limits the cell size and thus increases spectral efficiency. The 60 GHz absorption window contains up to 7 GHz of the frequency resource for deploying such networks.
Another advantage of using high-frequency ranges of MMD and OS is the possibility of creating very narrow directivity of antennas. Since, according to the physical laws of the formation and propagation of electromagnetic waves, with a decrease in the wavelength, it becomes possible to reduce the angle of the antenna aperture. The creation of narrowly directed emissions (for MMD of several degrees and even fractions of one degree) is associated with the possibility of implementing the MIMO (Multiple Input Multiple Output) technology of multipath signal propagation, which also increases the performance and energy efficiency of such systems.
The regularities of the propagation of MMD and OS in the atmosphere, in space, other environments, in urban scenarios are still being studied. The principles of modeling channels in the millimeter-wave range differ from models in other lower frequency radio bands, for example, 800 MHz-5 GHz. The main features of wave propagation are weak amplification due to diffraction, propagation in the line of sight, absorption in the atmosphere (Fig. 2), especially in the absorption windows of the atmosphere. In the region of 100 GHz, the phenomena of re-emission in the atmosphere are studied [9].

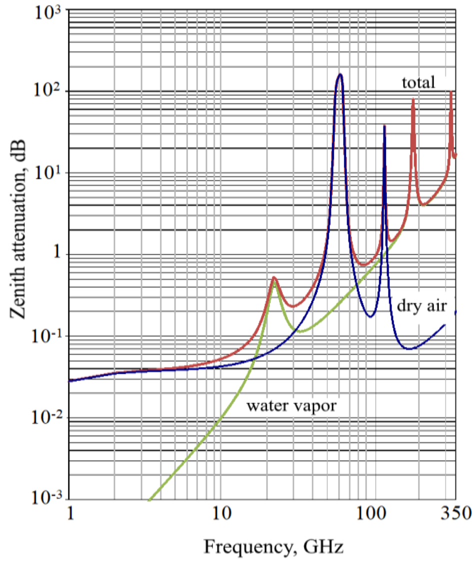

Figure 2. Total zenith attenuation, attenuation in dry air and water bath (pressure = 1013.25 hPa, temperature 15° C; water vapor density 7.5 g/m^3)

The use of OS and MMD is also planned for use in non-terrestrial communication systems. For example, in the second stage Starlink project, SpaceX aims to launch more than 7,500 vehicles that will begin to operate in the V-band (40 GHz - 75 GHz) at an altitude of 340 km [10].
For space communication systems, where there is no atmospheric absorption of signals, the best option is to use OS. Satellite optical communication lines with terrestrial stations in atmospheric transparency windows are also one of the promising solutions. (Fig. 3 [11]).
The use of OS, MMD and low-frequency classical ranges (300 MHz - 24 GHz) in open systems at different levels of non-terrestrial and terrestrial systems can be adapted under the influence of atmospheric disturbances and solar radiation.
For high MMD radio frequencies, there are various nonlinear signal distortions associated with the inhomogeneity of the atmosphere, and mainly with the nonlinear characteristics of the transmitting and receiving equipment. Therefore, complex multi-level methods of processing information signals, used, for example, in the decimeter range to increase the throughput, cannot be applied to wireless systems in MMD and OS, especially over long distances. Currently, new waveforms of signal waveforms and modulation schemes, coding in MMD and OS are being developed. So, the most promising for avoiding nonlinear signal distortions are considered pulsed ultra-wideband modulation methods, spatial multi-beam

multiplexing, cognitive spectrum methods (Software defined radio, SDR).

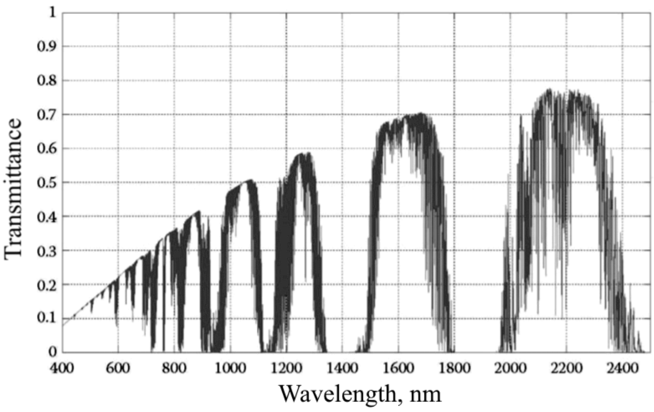

Figure 3. The transmittance of the atmosphere depending on the wavelength

4. Modeling the energy budget (potential) of a satellite communication channel

Modeling of the channel energy budget is based on the calculation of channel loss and noise. It is also necessary to consider the marginal constraints associated with the physical fundamental constraints. With an increase in the working radio frequency, noise parameters increase, limiting the value of the output power, transmission distance and bandwidth. The use of the optical spectrum and high-frequency radio bands in open systems has features associated with high directivity of radiation, absorption, propagation within the line of sight.

The energy potential (*PE*) of the radio channel in general is determined by the upper limit of the difference between the transmitter power (P_{TX}) and the receiver sensitivity ($P_{\text{RX-sens}}$) [11]:

$$P_{\text{TX}}\left[\text{dBm}\right] - P_{\text{RX-sens}}\left[\text{dBm}\right] = PE\left[\text{dBm}\right]. \quad (1)$$

The receiver sensitivity or the minimum allowable signal power at the receiver input is related by the ratio [10]:

$$\frac{P_{\text{RX-sens}}}{\left(N_{\text{int}} + N_{\text{TX}} + N_{\text{RX}}\right)} = \frac{P_{\text{S}}}{N}, \quad (2)$$

P_{S}/N is the denotes the ratio of carrier power to noise power required for demodulation; N_{TX} is the noise power of the signal source, which includes not only thermal noise, but also other components associated with the signal generation method; N_{TX} loss of signal power in the receiver; N_{int} is the signal can be properly recovered if its power at a distance *d* from the transmitting antenna exceeds the sensitivity of the receiver, that is, when $P_{\text{RX}} - P_{\text{RX-sens}} \geq 0$.

The signal in the radio channel between the terrestrial and satellite stations undergoes several stages of fading. Signal propagation can be carried out within the line of sight (LOS) or non-line of sight (NLOS) with a probability that depends on the environment (for example, urban or rural scenario) and the elevation angle α of the satellite. The model for calculating the loss (*PL*) in a space radio channel according to the recommendations of 3GPP [12] consists of the following elements:

$$PL\left[\text{dBm}\right] = PL_e + PL_b + PL_g + PL_s. \quad (3)$$

PL_e is the building entry loss, PL_b is the basic path loss, PL_g is the attenuation through atmospheric gases and PL_s is the signal attenuation due to ionospheric or tropospheric scintillation.

In the case of a satellite NLOS communication channel with an internal terrestrial terminal, according to 3GPP building entry loss PL_e, building entry loss is calculated as a cumulative probability distribution function *p*:

$$PL_e\left(p\right) = 10\log\left(10^{0.1A} + 10^{0.1B} + 10^{0.1C}\right), \quad (4)$$

where the parameters *A*, *B* and *C* depend on the carrier frequency f_c, the type of building, location inside the building and movement in the building, as described in [12].

Attenuation due to atmospheric gases PL_g is described as a function of carrier frequency f_c, placement angle *α*, satellite orbital altitude h, and water vapor density (i.e., absolute humidity). In particular, the PL_g parameter is calculated as:

$$PL_g(\alpha, f_c) = \frac{A_{\text{zenith}}(f_c)}{\sin\alpha}. \quad (5)$$

In (6), $A_{\text{zenith}}(f_c)$ is zenith attenuation (i.e., attenuation at a point directly above the observer on Earth (Fig. 4), due to dry air (oxygen induced by nitrogen pressure and non-resonant Debye attenuation) and water vapor.

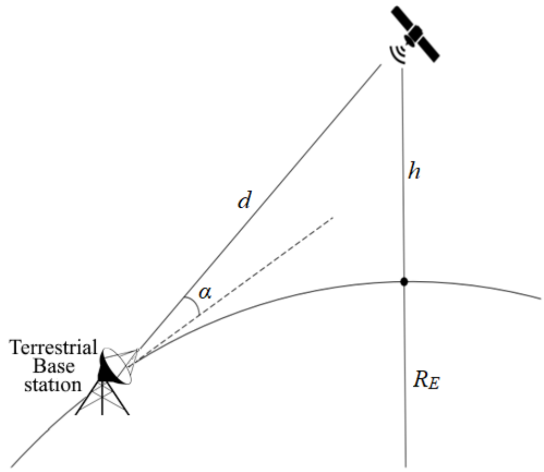

Figure 4. The concept of signal transmission between a satellite and a terrestrial station, R_E is the Earth's radius, *h* is the altitude of the satellite's orbit, *α* the angle of elevation, *d* is the distance between the satellite and the terrestrial station

Recommendation ITU-R P.676 [13] presents the corresponding dependence $A_{\text{zenith}}(f_c)$ for carrier frequencies from 1 to 350 GHz (Fig. 2), from which it can be seen that under normal atmospheric conditions it is below 10 dB. In hydrometeors, signal attenuation is also calculated by various functions and parameters for terrestrial and satellite systems.

It should be noted that for satellite communication lines the greatest influence on signal attenuation is exerted by the lower layers of the atmosphere up to 2 km.

Scintillation corresponds to rapid fluctuations in the amplitude and phase of the signal. Depending on the carrier frequency, ionospheric and/or tropospheric scintillation can affect satellite communications. That is, the phenomena of ionospheric (tropospheric) scintillation are applicable only for communications in the range below 6 GHz. Therefore, for normal conditions at mid-latitudes (from ± 20° to ± 60°), strong scintillation levels are rarely observed, and it can be assumed that PL_s = 0. For all other latitudes, in accordance with [12]:

$$PL_s(f_c) = \frac{27.5 \cdot S_4^{1.26}(f_c/4)^{-1.5}}{\sqrt{2}}, \quad (6)$$

S4 is the amplitude scintillation index [11] and depends on the latitude. At low latitudes (between ± 20°, that is, in the equatorial regions), scintillation occurs due to large volumes of depleted ionization created by convective plasma processes, respectively $S_4 = 0 \div 4$. At high latitudes (above ± 60°), scintillation mainly occurs from the edge of the outer Van Allen belt, respectively $S_4 = 0 \div 7$. The influence of tropospheric scintillations in 3GPP is characterized as a function of $PL(f_c, \alpha)$, in contrast to ionospheric scintillations, increases with an increase in the carrier signal frequency, especially at frequencies above 10 GHz. In this case, signal fluctuations are caused by sudden changes in refractive index due to changes in temperature, water vapor content and barometric pressure.

The PL_b value in formula (3) is determined in accordance with 3GPP TR38.901 [12] standard free space loss (FSPL), shadow attenuation (SF) and clutter loss (CL) associated with signal re-reflections from interference, and are expressed as:

$$PL_b(d, f_c, \alpha) = FSPL(d, f_c) + SF + CL(\alpha, f_c), \quad (7)$$

The FSPL is taken from the Friis model, depending on the carrier frequency f_c in GHz and the distance d:

$$FSPL(d, f_c) = 32.45 + 20\log(f_c) + 20\log(d). \quad (8)$$

The patterns of propagation of MMD radio waves are fundamentally different from propagation in the ranges in which modern 3G and 4G communication systems operate. The scattering of the MMD signal occurs when it is reflected from the rough concrete surfaces of buildings, when the MMD radio wave passes through the crowns of trees, etc. The construction of empirical models is based on finding a function that approximates measurements taken in a certain area of interest. Thus, the reference approach is the use of the Friis propagation model, which uses an empirical relationship $D\lambda^2 = 4\pi A_{eff}$ that is true for narrowband systems [14]. $D_{\text{TX}}(\theta)$ is antenna directivity, θ is antenna aperture angle, A_{RX} is effective receiving antenna area $(A_{\text{RX}} = KA_{phys})$ 0<K<1, A_{phys} - antenna physical area). With decreasing wavelength, the directivity of the antennas increases, so for phased antenna arrays, the angular beam width corresponds to $\theta \approx \sqrt{\lambda/Nb}$ [15], where N is the number of radiating elements, b is the distance between these elements.

For high frequency radio and optical wireless systems in future projects, it would be best to use one channel model. The comparability of the parameters of gain and loss in the channel is very close both for signals in MMD and in OS. The patterns of propagation of MMD waves have more quasi-optical propagation characteristics compared to the classical 3G and 4G bands.

This article proposes a quasi-optical model that takes into account the signal loss associated with the spatial divergence of the signal:

$$P_{\text{RX}} = P_{\text{TX}} \frac{D_{\text{TX}}(\theta) A_{\text{RX}}}{4\pi d^2} \approx P_{\text{TX}} \frac{4A_{\text{RX}}}{\pi\theta^2 d^2}, \quad (9)$$

where the factor $\frac{4\pi d^2}{D_{\text{TX}}(\theta)}$ determines the signal loss associated with the divergence of the radiation (Fig. 5).

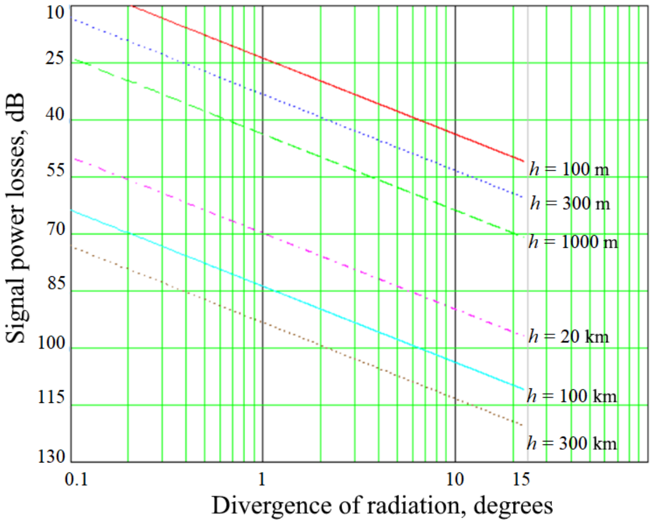

Figure 5. Dependence of the antenna aperture angle and signal power losses associated with the divergence of radiation for different heights h of the satellite location

Using (3) and (9) you can get:

$$P_{\text{RX}}[\text{dB}] = P_{\text{TX}} - PL = P_{\text{TX}} - 10\lg\left(\frac{4\pi d^2}{D_{\text{TX}} A_{\text{RX}}}\right) - \quad (10)$$
$$-SF - CL(\alpha, f_c) - PL_e - PL_g - PL_s.$$

In (10) d is expressed in meters as a function of the Earth's radius R_E, the satellite orbit altitude h and the satellite angular position (elevation angle) α (Fig. 6), therefore:

$$d = \sqrt{R_E^2 \sin^2\alpha + h^2 + 2hR_E} - R_E \sin\alpha. \quad (11)$$

The channel loss function $CL(\alpha, f_c)$ simulates the signal power attenuation caused by existing buildings and objects on the ground. Corresponding CL and SF values are given in 3GPPTR [12] for exit elevation angles for various building layout scenarios.

To assess the interrelated values of spectral and energy capacity, bandwidth, the Shannon equation is usually taken as a basis.

$$C = B\log_2(1 + SNR), \quad (12)$$

where the signal-to-noise ratio (SNR) is determined in accordance with (2) as $SNR = P_{\text{RX}} / (N_{\text{int}} + N_{\text{TX}} + N_{\text{RX}})$.

We assume that if the SNR is below a predetermined threshold of 0 dB, then the Earth-to-satellite link cannot be established, in which case we set the Shannon bandwidth to 0.

Spectrum below 6 GHz offers limited capacity (i.e. <500 Mbps), which may not be sufficient for new applications and technologies. Network performance can be increased by using the frequency resources of MMD and OS, which are also associated with directional amplification (> 50 dB, which is typical for modern satellite antenna technologies). The divergence of the light beam of a modern laser can reach 10 mrad. It is also known that for high-frequency technologies, as the transmitter power increases, the noise power increases. This topic is analyzed, for example, in [6-8], and has a large information and computing capacity. In this work, this issue is not analyzed.

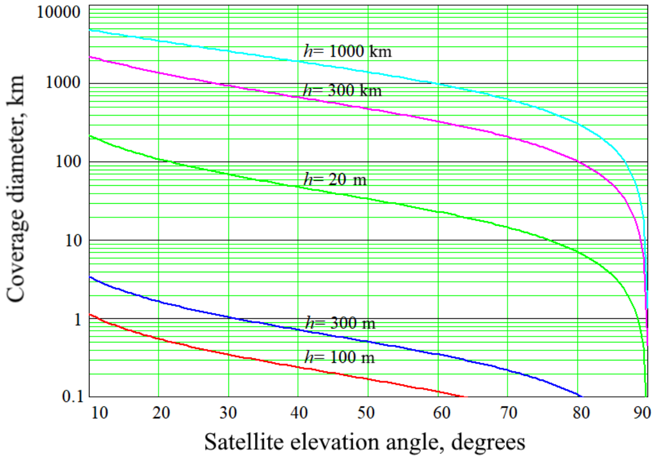

Figure 6. Dependence of the angle of elevation of the satellite on the diameter of the coating without taking into account refraction

5. Comparison of the effectiveness of various configurations of a multi-level satellite communication system between terrestrial and non-terrestrial segments

The peculiarities of the structure of the atmosphere and the advantages of satellite technologies allow the use of multilevel altitude models, which can be used to increase the throughput.

Opportunities for increasing productivity using multi-level high-altitude communication systems are based on the following factors:

- in one path of using MMD, OS, LTE bands, fiber optic lines, depending on the structure of the atmosphere, weather conditions, territorial location;
- in stratospheric platforms and UAVs, it is envisaged to increase the signal power through the use of solar energy, increase the directivity (gain) of the antenna, and use of MIMO technology;
- the space (airborne) station can perform: filtering and conversion of radio frequencies, demodulation/decoding, switching/routing, coding/modulation.

The average throughput of open terrestrial optical systems is 2 Gbps. However, with the improvement of methods of optoelectronic signal processing, the transmission speed can grow up to hundreds (and more) Gbit/s.

Consider a downlink from a satellite to an earth station. The parameters for modeling the Shannon capacity are presented in Table 1.

Optical space communication on Earth-satellite links and between satellites has been successfully used for a long time [16-18]. Modern advances in space technology and photonic technology are opening a new chapter for optical space communications. The bandwidth of the optical channel helps to reduce signal latency and maintain real-time mode, which is necessary for many important applications. But despite the great potential of FSO communication (free-space optics), its performance is limited by side effects (namely, absorption, scattering and turbulence) of the atmospheric channel, which make the channel a random function of space and time.

For this reason, FSO requires tracking and very precise targeting of the optical radiation to the receiver. With FSO, visibility can be greater than 10 miles in clear weather conditions.

Experimental results [19] demonstrated throughput up to 1.25 Gbit/s for the downlink satellite-to-Earth FSO channel, as well as for HAP-HAP up to 10 Gbit/s. It is assumed that with the improvement of modulation schemes, the bandwidth of the FSO wireless network can be increased even up to 100 Gbps [19-23]. The power consumption of onboard satellite antennas is supposed to be from 0.5 to 5 W, depending on the data transfer rate over a distance of up to several 1000 km [19]. MIMO FSO systems can also significantly increase performance.

Table 1. Model parameters

Parameter	Value				
Elevation (elevation) angle of the satellite, degrees	10, . . . , 90 degr.				
Satellite LEO altitude	2000 - 300 km				
HAPs	20 km				
UAV	1 km – 100 m				
Carrier frequency fc	2 GHz	6 GHz	28 GHz	70 GHz	0.36 PHz
Channel width B	200 MHz	500 MHz	1 GHz	3 GHz	100 GHz
Antenna aperture angle (beam width)	5 degr.	3 degr.	0,5 degr.	0,3 degr.	$6.7x10^{-4}$ degr.
MMD transmitter power	33 dBm				
Ground base station receiving antenna aperture area	3 m^2	3 m^2	1,5 m^2	1,5 m^2	0,2 m^2
LEO satellite receiving antenna aperture area	0.5-1 m^2	0.5-1 m^2	0.5-1 m^2	0.5-1 m^2	0,2 m^2
Signal to noise ratio threshold	0 dB				
Signal modulation method	OOK, PPM				
Distance between ground base station and user for urban scenario	300 m, 100 m				
Latitude	35 °				
Earth radius RE	6371 km				
Temperature T	288.15K				
Concentration of water vapor	7.5 g/m^3				
Air pressure;	1013.25 hPa				
Segmenting Options	1 segment (1000 km, 300 km): Satellite-Earth 2 GHz, 6 GHz, 28 GHz, 70 GHz,				
	2 segments: Satellite (300 km) –HAPs (20 km) –Earth				
	3 segments: Satellite (300 km) -HAPs (20 km) - LAPs (100 m) -Earth				
	4 segments: Sputnik-HAPs-LAPs (2 km) - LAPs (100 m) -Earth				

Figures 7-9 show the calculations of Shannon's information capacity for multilevel satellites (HAP, UAV).

Intermediate HAP (UAV) provides increased throughput by amplifying the signal from the uplink satellite before it is sent to the ground, while providing faster deployment and lower costs compared to space stations. Figure 7-9 also provides a comparative representation of the operation of multilevel systems in the atmospheric transparency windows of 28-52 GHz, 70-80 GHz and in the OS.

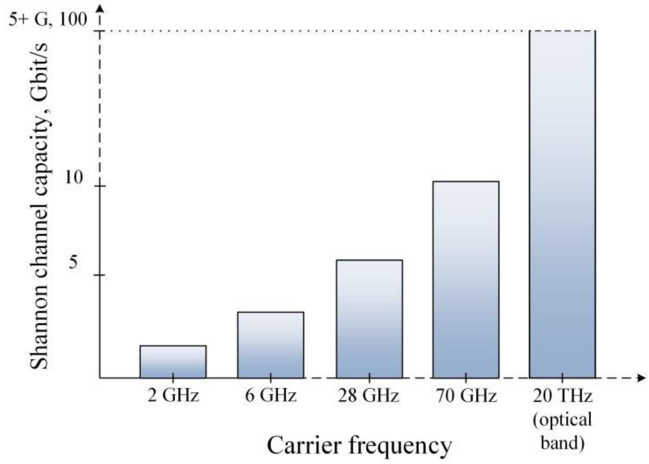

Figure 7. Comparative representation of the Shannon channel capacity for the LEO-Earth satellite line on different radio and optical bands

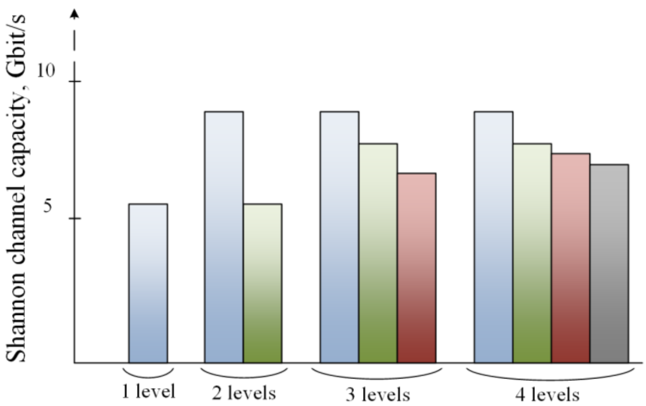

Figure 8. Comparative representation of the Shannon channel capacity for a multi-level scenario of a satellite communication line operating in the 28 GHz band: LEO-BS_E, (terrestrial base station), 2 levels LEO-HAP-BS_E, 3 levels LEO-HAP-UAV-BS_E, 4 levels LEO-HAP-UAV1 (1 km)-UAV2 (100 m)-BS_E

6. Future Discussions

Wireless communication in MMD and OS has great potential for use in space communication systems. These technologies have the advantages of using azimuth line-of-sight channels in comparison with terrestrial ones. For example, the total zenith attenuation can be much less than the linear attenuation in the lower atmosphere. It also has advantages in terms of reconfiguration virtuality, coverage area and energy (spectral) efficiency. A sudden drop in communication quality due to atmospheric phenomena, including severe atmospheric turbulence, leads to the need for adaptive dynamic beam steering, which also leads to a decrease in the use of resources, both frequency and energy. Wireless and fiber optic communication systems have similarities in the operating wavelength range, processing methods. The methods of radio photonics can be applied to wireless communication systems, where the technology of converting radio waves into optical, including the terahertz range, can be used.

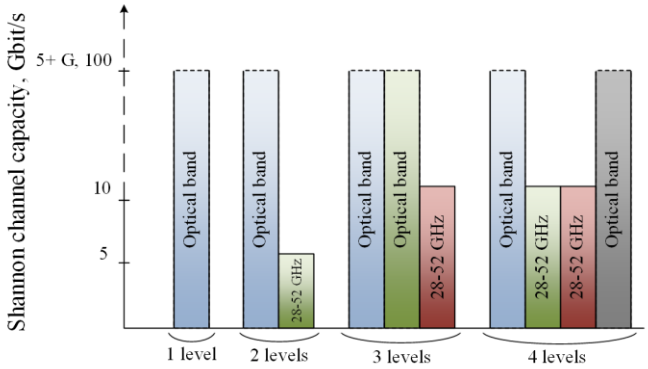

Figure 9. Comparative presentation of Shannon channel capacity for a multi-level scenario of a satellite communication link: 1 level LEO-BS_E(terrestrial station), 2 levels LEO-HAP-BS_E, 3 levels LEO-HAP-UAV-BS_E , 4 levels LEO-HAP-UAV1 (1 km)-UAV2 (100 m)-BS_E on various radio and optical bands

Hybrid use of MMD and OS in space communication systems, multi-level configuration of the location of satellite repeaters, including HAP and UAV, fiber-optic lines, advanced signal processing methods can provide high-speed communication in almost any weather conditions anywhere on the Earth. The implementation of high-speed radio links is largely associated with advances in the field of photonics. For example, optoelectronic methods of radiation formation in phased antenna arrays, the use of promising modulation formats, such as high-order QAM, pulse modulation of an optical signal with polarization effects, MIMO PAR technologies, tracking methods.

7. Conclusions

Non-terrestrial networks are being explored as a key component of the 6G fabric to support global, ubiquitous and uninterrupted connectivity, and to overcome the coverage constraints of 5G deployments.

The proposed system of multi-level integrated architecture of space communications can be considered for 5G+ networks. Sharing radio and optical spectrum, mobile network architecture with repeaters at different altitudes to adapt weather conditions, required bandwidth, etc. contributes to an increase in throughput of hundreds of gigabits per second. As part of future work, it is necessary to combine the principle, parameters of terrestrial and non-terrestrial telecommunications, modulation/multiplexing methods, delay time and coverage.

References

[1] M. M. Mohialdeen, V. Zaika, Yu. Khlaponin, L. Berkman, K. Polonskyi, O. Turovsky, “Methods for Assessing the impact of Bandwidth of Control Channels on the Quality of Telecommunications Networks in the Transmission of Data Packets of different types,” International Journal of Communication Networks and Information Security (IJCNIS), Vol. 13, No. 2, pp. 220-229, 2021. DOI: https://doi.org/10.54039/ijcnis.v13i2

[2] M. Giordani, M. Polese, M. Mezzavilla, S. Rangan, and M. Zorzi, "Toward 6G Networks: Use Cases

and Technologies," IEEE Communications Magazine, Vol. 58, No. 3, pp. 55–61, 2020.

[3] F. Babich, M. Comisso, A. Cuttin, M. Marchese, and F. Patrone, "Nanosatellite-5G Integration in the Millimeter Wave Domain: A Full Top-Down Approach," IEEE Transactions on Mobile Computing, Vol. 19, No. 2, pp. 390–404, 2020.

[4] M. A. Khalighi, M. Uysal, "Survey on Free Space Optical Communication: A Communication Theory Perspective," IEEE Communications Surveys & Tutorials, Vol. 16, No. 4, pp. 2231–2258, 2014.

[5] M. Giordani, M. Zorzi, "Non-Terrestrial Networks in the 6G Era: Challenges and Opportunities," IEEE Network, pp. 12–19, 2020.

[6] J. Yu, X. Li, and W. Zhou, "Tutorial: Broadband fiber-wireless integration for 5G+ communication," APL Photonics, Vol. 3, No. 11, p. 111101, 2018.

[7] S. Jia, "THz photonic wireless links with 16-QAM modulation in the 375-450 GHz band," Optics Express, Vol. 24, No. 21, p. 23777, 2016.

[8] V. J. Urick, C. S. Sunderman, J. F. Diehl, N. D. Peterson, "W-Band Technology and Techniques for Analog Millimeter-Wave Photonics," Defense Technical Information Center, 2015. [Online]. Available: https://apps.dtic.mil/sti/pdfs/ADA622901.pdf

[9] V. Petrov, M. Komarov, D. Moltchanov, J. M. Jornet, Y. Koucheryavy, "Interference and SINR in Millimeter Wave and Terahertz Communication Systems With Blocking and Directional Antennas," IEEE Transactions on Wireless Communications, Vol. 16, No. 3, pp. 1791–1808, 2017.

[10] J. Loughran, "Starlink launches 60 more satellites but commercial service faces delays," Engineering and Technology (IET), 2020. [Online]. Available: https://eandt.theiet.org/content/articles/2020/11/starlink-launches-60-more-satellites-but-commercial-service-faces-delays/

[11] N. J. Veck, "Atmospheric Transmission and Natural Illumination (visible to microwave regions)", GEC Journal of Research, Vol. 4, No. 3, pp. 209 – 223, 1985.

[12] Y. A. Kremenetskaya, E. R. Zhukova, N. V. Gradoboeva, D. A. Lyubas, B. V. Saenko, "Physical aspects of modeling a radio channel and noise in the millimeter range," Telecommunications and Information Technologies, Vol. 1, No. 2, pp. 60-71, 2018.

[13] 3GPP, "Solutions for NR support for Non-Terrestrial Networks (NTN)," TR 38.821 (Release 16), 2020.

[14] ITU-R, "Recommendation ITU-R P.676," 2005. [Online]. Available: https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.676-6-200503-S!!PDF-R.pdf

[15] M.P. Dolukhanov, Propagation of radio waves. Moscow: Communication, 1972.

[16] R.S. Hansen, Fazirovannye antennye reshetki (Phased antenna arrays). Moscow: Tekhnosfera, 2012, 560 p.

[17] T. Aruga, K. Araki, T. Igarashi, F. Imai, Y. Yamamoto, and H. Sakagami, "Earth-to-space laser beam transmission for spacecraft attitude measurement," Applied Optics, Vol. 23, No. 1, p. 143, 1984.

[18] T. Aruga, K. Araki, R. Hayashi, T. Iwabuchi, M. Takahashi, and S. Nakamura, "Earth-to-geosynchronous satellite laser beam transmission," Applied Optics, Vol. 24, No. 1, p. 53, 1985.

[19] K. Araki, T. Itabe, M. Takabe, T. Aruga, H. Inomata, "Experiments on CO2 laser beam transmission from ground to geostationary meteorological satellite," Laser Sensing Syimposium, Japan, pp. 47–48, 1988.

[20] H. Kaushal, G. Kaddoum, "Optical Communication in Space: Challenges and Mitigation Techniques," IEEE Communications Surveys & Tutorials, Vol. 19, No. 1, pp. 57–96, 2017.

[21] M. Singh, J. Malhotra, M. S. Mani Rajan, D. Vigneswaran, M. H. Aly, "A long-haul 100 Gbps hybrid PDM/CO-OFDM FSO transmission system: Impact of climate conditions and atmospheric turbulence," Alexandria Engineering Journal, Vol. 60, No. 1, pp. 785–794, 2021.

[22] C.-Y. Li, X.-H. Huang, H.-H. Lu, Y.-C. Huang, Q.-P. Huang, and S.-C. Tu, "A WDM PAM4 FSO–UWOC Integrated System With a Channel Capacity of 100 Gb/s," Journal of Lightwave Technology, Vol. 38, No. 7, pp. 1766–1776, 2020.

[23] X.-H. Huang, "Two-way wireless-over-fibre and FSO-over-fibre communication systems with an optical carrier transmission," Laser Physics, Vol. 28, No. 7, p. 076207, 2018.