FSO Communication Systems with the Integration of a Hybrid Wireless Radio Frequency System

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ABSTRACT: *This work has studied the acceptance of the operation of FSO communication systems with the integration of a hybrid wireless radio frequency system. The system efficiency is tested with many experiments depending on the meteorological conditions. This paper has outlined an algorithm for switching the constitutive systems, depending on the specific meteorological condition. It is based on the received power of each subsystem (FSO and RF) of the hybrid FSO/RF communication system.*

Keywords: Free Space Optics, FSO, Radio Frequency, Hybrid Systems, Telecommunications

Received: 3 March 2023, Revised 4 July 2023, Accepted 17 July 2023

DOI: 10.6025/jes/2023/13/3/68-74

1. Introduction

In the last decade the Free Space Optics (FSO) communication systems became alternative of the fibber optic systems. In these years the technological progress leads to their serious development that allows their wider usage. The four channel FSO system works successfully on distance of more than 28 km with data rate 2.5 Gbps per channel or 10 Gbps overall [1].

In USA, more than 90 % of business costumers are situated on about one mile distance from some high-speed fiber-optic network, but only 19% have access to it. That is mainly caused by high cost of new networks installation. This gives to FSO systems very big potential market. Their wider usage in telecommunications, for example by Internet providers, is limited by relatively low and dependent on distance link availability. That low availability is connected with comparatively rapid and casual changes of atmospheric transparency that are due to unpredictable changes of meteorological conditions during the time. If it is found a way to increase link reliability of FSO from typical 97-98 % to at least 99.9 %, the problem will be solved.

Besides FSO systems, that operate in visible and near infrared diapason, the wireless communication systems use millimeter radio waves also. A practical solution for increasing link availability of FSO is its integration whit a radio frequency (RF) communication system in a hybrid FSO/RF system. The radio subsystem has lower data rate, but has higher stability against bad meteorological conditions like thick fog.

This paper presented analytical expressions and results for estimation of the power budget of systems, operating in optical wavelength and millimeter frequency ranges. The potentialities of these systems are compared by using a numerical experiment. An algorithm for switching of FSO and RF subsystems depending on meteorological conditions is suggested. Numerical and graphic results of the investigation are presented.

2. Theoretical Analysis

The electromagnetic waves (EM) are absorbed in atmospheric gases, especially in water molecules, carbonic dioxide, oxygen and ozone, when they propagate in Earth's atmosphere. For decrease the influence of this effect the wireless communication systems use frequencies (wavelengths) situated in so-called "transparency windows of the atmosphere".

The EM waves are also absorbed and scattered quite frequency selectively by atmospheric aerosol, anthropogenic or natural, like fog, cloud, smoke and hydrometeors (rain, snow etc.). The attenuation for some wavelengths is so great, that sometimes the connection can interrupt completely even if the link distance is short. When a hybrid communication system is used its link availability has to be higher than of each containing subsystem.

There are some main physical reasons for higher functionality of hybrid FSO/RF communication systems. In frequency range above 10 GHz radio waves are hardly influenced by the hydrometeors and mainly by the rain, because it can be more intensive by the snow. Because rain drops size (0,1 mm to 7 mm) is in the same order as wavelength, the radio wave attenuation in rain is considerable. The link availability of a FSO system is influenced mainly by the fog, what is closely related with visibility S_m [2, 3]. The fog particles have size of the order of microns and part of microns (typical 1 μm to 20 μm), i.e. they are commensurable to optical radiation wavelength and therefore the optical wave attenuation in presence of fog is hardly significant. The probability of simultaneously presence of fog and rain is very small, for that reason it can be expected that for a hybrid FSO/RF communication system the disadvantages of its two parts will compensate each other and the overall availability of the system will increase significantly.

The functionality of the communication systems, working in wavelengths of millimeter and centimeter ranges, is determined by some factors as: the effective isotropic radiated power – EIRP, that depends on transmitter power, feeder losses and antenna gain; propagation losses, including free space losses, diffraction losses, attenuation caused by hydrometeors and gaseous molecules; receiver sensibility – given as minimal power in the input of the receiver that guaranteed fixed value of BER (it is often chosen 10^{-6}).

The atmospheric gaseous absorption losses are well described in the literature and they depend mainly on frequency [4]. The rain attenuation depends on frequency and rain rate and can be obtained by using the methods described in [5]. The scattering losses are due to troposphere's scattering caused by troposphere's density changes and rain scattering.

The power in the input of a radio receiver P_r [dBm] can be calculated by expression

$$P_{\mathrm{r}} = P_{\mathrm{t}} + G_{\mathrm{t}} - L_{\mathrm{t}} - L_{\mathrm{f}} - L_{\mathrm{a}} - L_{\mathrm{r}} + G_{\mathrm{r}}, \quad (1)$$

were P_t [dBm] is the transmitter's power; G_t (G_r) [dBi] – transmitter (receiver) antenna gain; L_t (L_r) [dB] – transmitter's (receiver's) tract losses; L_f [dB] – free space losses; L_a [dB] – atmospheric losses (in atmospheric gases and hydrometeors) [4, 5].

The antenna gain G and free space losses can be calculated by relations

$$G = \frac{4\pi\eta A_{\mathrm{g}}}{\lambda^2} \quad (2)$$

and

$$L_{\mathrm{f}} = \left(\frac{4\pi z}{\lambda}\right)^2 \quad (3)$$

where η is the coefficient of antenna area usage, that usually has values from 0,55 to 0,75; A_g [m^2] is geometrical area of the antenna aperture; λ[*m*] is wavelength in free space; *z* [*m*] is distance between the transmitter and the receiver (link distance).

The signal-to-noise ratio SNR can be calculated by using determined by Eq. (1) value of received power -

$$SNR = P_{\mathrm{r}} - S_{\mathrm{r}} + A \ \ [\mathrm{dB}] \quad (4)$$

We need to know the receiver's sensibility S_r[dBm] and to choose a proper value of power reserve *A*[dB]. The sensibility describes receiver's internal noises for given frequency band (the manufacturer's catalog value can be used). The power reserve is necessary for the cases when unpredictable losses appear. Usually its typical value is 10 to 15 dB.

The link budget for FSO system was described in our previous works [6, 7]. In this work we present only final results what we use in the numerical experiments. For simplification of used mathematical model we assume that: the region of Earth's atmosphere that is part of the FSO communication channel is homogeneous; the laser beam is with Gaussian distribution in transmitter's aperture and the conditions in the atmosphere are suitable for its preservation during the propagation; we introduce a correction for current laser beam radius that takes account of additional extension of the laser beam compared with theoretical; the noise due to the background radiation is neglected [9]; analog modulation of the laser optical beam is performed in the transmitter.

Therefore the average value of received signal optical power in the input of photo detector is

$$\Phi_{\mathrm{PD}} = \frac{1}{2}\Phi_{\mathrm{L}}\tau_{\mathrm{t}}\tau_{\mathrm{r}}\exp\left\{-z[\mathrm{km}]\frac{3{,}92}{S_{\mathrm{m}}[\mathrm{km}]}\left(\frac{\lambda[\mu\mathrm{m}]}{0{,}55}\right)^{-0{,}585\sqrt[3]{S_{\mathrm{m}}[\mathrm{km}]}}\right\}.$$

$$.\frac{1-\exp\left(-2\dfrac{R_{\mathrm{r}}^2}{\rho_z^2(z)}\right)}{1-\exp(-2)}, \quad (5)$$

where Φ_L [W] is the laser power; τ_{t} and τ_{r} are respectively the transmitter's and the receiver's optical systems transparency; *z* is the link distance; S_m is the meteorological visibility of the atmosphere; λ is the wavelength; R_r [*m*] is the transmitter's antenna radius; ρ_z [m] is current Gaussian laser beam radius. When ρ_z is calculated the initial radius of laser beam ρ_0, the wavelength λ and the link distance *z* are used. The above mentioned correction is also applied.

The signal-to-noise ratio in the output of the receiver can be calculated with taking in account quantum noises, thermal noises and dark current of photo-detector by using the formula

$$SNR = \frac{(\Phi_{\mathrm{PD}}.R_{\mathrm{D}})^2}{2.e.\Delta f.I_{\mathrm{D}} + 2.e.\Delta f.I_{\mathrm{S}} + \dfrac{4.k_{\mathrm{B}}.T.\Delta f}{R_{\mathrm{L}}}}. \quad (6)$$

In eq. (6) R_D [*A/W*] is the integral sensibility of photodetector; *e* [*C*] is the electron's charge; Δ*f* [Hz] is the frequency band of the photo-detector; *ID* [*A*] is the dark current of the photo-detector; I_S [*A*] is the signal current; k_B [*J/K*] is the Boltzmann constant; T [°K] is the temperature of the detector; R_L [Ω] is the load in the photo-detector's circuit.

In the graphics we use the logarithmical values of signal-tonoise ratio SNR [dB].

Very important part of the hybrid FSO/RF system functionality is the procedure of subsystems switching and the choice of a parameter and thresholds that will be used in this switching. There are various variants. In dependence on the chosen value of BER that is related to the applied modulation technique, we can determine necessary SNR. Further by using this signal-to-noise ratio we can calculate the minimal value of the received power that guaranteed system's functionality. The easiest way to realize a system, what takes decision for switching of subsystems is to use the received power. In this case there is not a need of additional signal transformations and calculations. Furthermore it is good to use two different threshold levels and the level for switching $RF \rightarrow FSO$ has to be somewhat greater than the level for $FSO \rightarrow RF$ switching.

In this way we avoid the more frequently subsystems switching. This can cause significant data losses, because of lower data capacity of RF system. After switching, the inactive subsystem has to be in waiting regime.

The "International table for relation between visibility, meteorological conditions and attenuation" [3] can be used for fast estimation of the attenuation in one hybrid FSO/RF communication system in different weather conditions. Further the switching terms can be defined in one model FSO/RF system in dependence on the visibility [8]. The two different thresholds can be defined.

In a hybrid FSO/RF system the only uncontrolled variability in the link budget equation is the communication channel transparency. It depends on concrete meteorological conditions. A possible algorithm for switching and functionality control of the subsystems is by estimation of this variability. Then after comparison with previously given values or with dynamic determined ones, obtained by studying, the algorithm takes decision for switching. This is the approach we choose, and the switching algorithm is given on Figure 1.

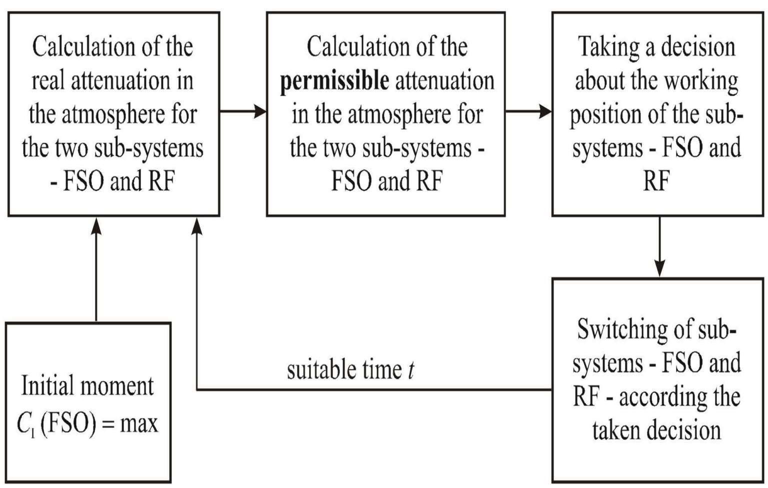

Figure 1. Subsystems switching algorithm

3. Numerical Experiments

For our numerical experiments we use the parameters' values typical for the real communication system. We fix a link distance z = 1,5 km because the typical hybrid communication system operates on distances in order of 1 km when the rain rate is from 2 mm/h to 100 mm/h or the meteorological visibility is from 0,1 km to 20 km. When we study the SNR dependence on the link distance z, we assume $z \leq 10$ km in case of clear atmosphere (S_m = 20 km).

The other parameters are as follow: for the RF subsystem we choose f = 2.4 GHz, with P_t = 5 dBm, $G_r = G_t$ = 15 dBi, $L_r = L_t$ = 3 dB,

L_f = 103,566 dB, S_r = - 90 dBm and f = 60 GHz, with P_t = 10 dBm, G_r = G_t = 41 dBi, L_r = L_t = 3 dB, L_f = 131, 525 dB, S_r = - 85 dBm; for FSO subsystem - Q = 532 nm, with R_L = 0,5 mW, S_t = 0,7, S_r = 0,9, R_r = 8 cm, T_0 = 2 cm, U = 2 mrad, R_d = 0,24 A/W, R_t = 5 kV, W_f = 1 GHz, I_d = 1.5 nA and Q = 850 nm, with R_L = 0,5 mW, St = 0,7, S_r = 0,9, Rr = 8 cm, T_0 = 2 cm, U = 2 mrad, R_d = 0,5 A/W, R_L = 5 kV, W_f = 1 GHz, I_d = 2 nA. The frequencies for R_F are chosen because they aren't object of license.

Calculated values of SNR for two subsystems of the hybrid FSO/RF system are shown on Figure 2, 3 and 4.

Figure 2 shows that even very weak rain influences seriously 60 GHz RF subsystem functionality. In other way the FSO subsystem keeps its functionality even in heavy rain conditions for two investigated wavelengths.

The drawings in Figure 3 show that in fog conditions the FSO subsystem performance decreases significantly without dependence on wavelength even for visibility S_m in order of 1 to 2 km. In other hand the RF subsystem will work stable even when the visibility S_m is about 30 m, although in this case SNR is relatively low.

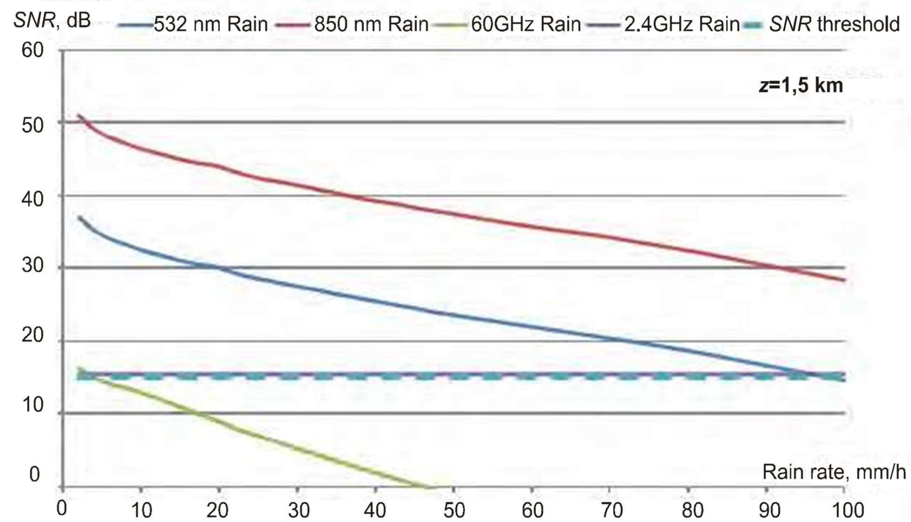

Figure 2. Hybrid FRO/RF system SNR dependence on the rain rate

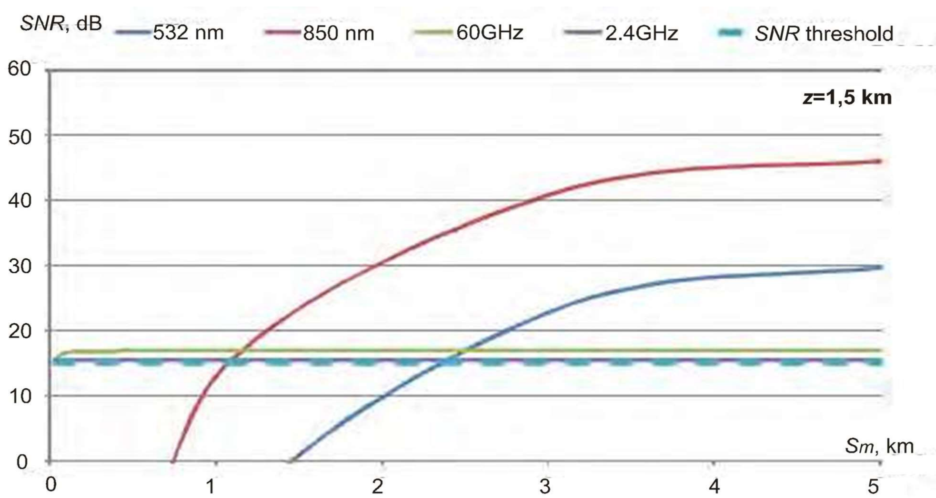

Figure 3. Hybrid FRO/RF system SNR dependence on the visibility

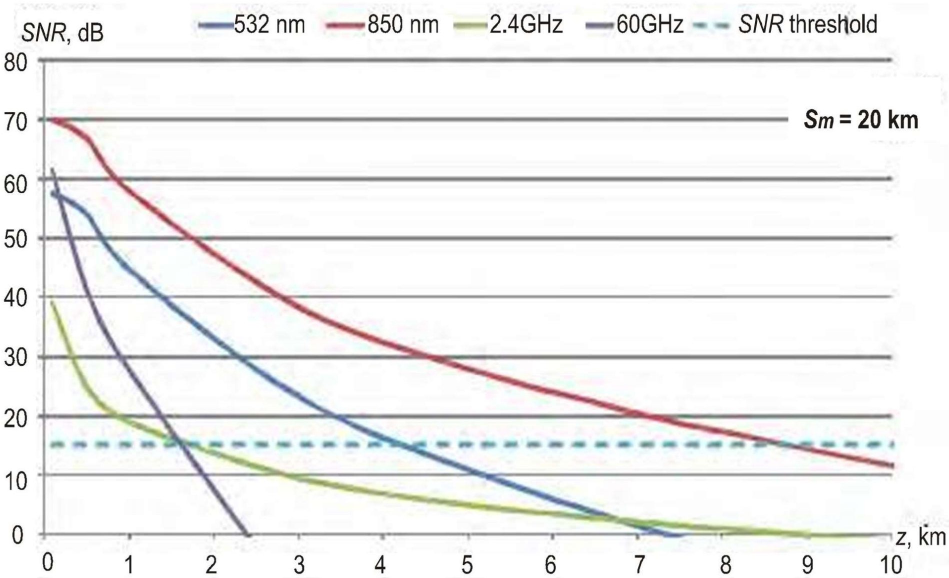

Figure 4. Hybrid FRO/RF system SNR dependence on the link distance

Figure 4 shows that when the atmosphere is clear (S_m = 20 km), the FSO subsystem has serious advantage over the RF one even for link distances from 4 km to 9 km.

4. Results Analysis and Conclusions

From applied drawings can be viewed that a heavy rain influences the FSO subsystem functionality much lower than the RF one. As expected the results show increase of optical power through the photo detector's aperture even in high values of rain rate. When RF subsystem uses frequency of 2.4 GHz the SNR is not affected both by the rain and fog but despite this it stands relatively low. It varies significantly only with increases of distance. The calculations give us a possibility to assess that in frequencies of 60 GHz the rain attenuation is considerable, compared to other frequencies, and it doesn't allow high speed communication in long distances. However the fog attenuation in this frequency is relatively low even when the visibility is very low. At the same time, despite relatively low fog attenuation for wavelength 850 nm according to 532 nm, we can't speak for independently working FSO system at these conditions. The very high attenuation of optical waves in fog then the visibility S_m < 0,5 km, is obvious.

For distances up to 2 km RF system works satisfactorily with data transfer, but for communications on distances from 2 to 10 km, FSO systems are more suitable. We can remark that they show better functionality in high visibility conditions. Therefore a hybrid FSO/RF system will rely more on the FSO subsystem. The determination of concrete intervals for work of each subsystem is object of further investigation. The desired system configuration depends on the meteorological conditions and the wanted availability.

It is obvious that a hybrid FSO/RF system contains parts that compensate their disadvantages each other. Therefore the overall availability time for a hybrid system will be significantly greater than for each containing subsystem one by one.

In our work we have chosen to use a SNR as criterion for link quality. This is motivated with our desire to avoid connection with used modulation technique. Nowadays when digital systems are used, the more attractive quantity is BER, what allows development of this investigation. The theoretical model can be also developed with taking into account some specific effects and phenomena like type of fog – continental or seaside for example. It is also possible to be studied a hybrid system by using real statistical, meteorological data and then to be formulated more accurately the interruption intervals and link availability for the concrete geographical region.

Acknowledgement

This work was supported under Project Nr DUNK-01/03 – 12.09 "University Scientific and Research Complex for Innovation and Transfer of Knowledge in Areas of Micro/Nano Technologies and Materials, Power Effectiveness and Virtual Engineering".

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