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**ЭВОЛЮЦИЯ РАДИОСВЯЗИ ПО ОПТИЧЕСКОМУ КАНАЛУ СВЯЗИ
В СВОБОДНОМ ПРОСТРАНСТВЕ С ИСПОЛЬЗОВАНИЕМ
МУЛЬТИПЛЕКСИРОВАНИЯ ПОДНЕСУЩИХ С АМПЛИТУДНОЙ
МАНИПУЛЯЦИЕЙ**

В беспроводных системах и сетях отмечается высокий спрос на радиосвязь по оптическому каналу связи в свободном пространстве (RoFSO) с широкой полосой пропускания и высокой скоростью передачи данных. Такая связь обеспечивает такую же скорость передачи данных, как в волоконно-оптических системах, но при меньшей стоимости на её развёртывание. Системы RoFSO реализуются комбинированием радиосигнала (RF) с оптическим сигналом для беспроводных каналов в свободном пространстве (FSO). Предлагается моделирование системы с мультиплексированием поднесущих с амплитудной манипуляцией (SCM/ASK) для оптической связи в свободном пространстве. В системе Скорость передачи данных принята равной 1 Гбит/с. Электронный амплитудный модулятор настроен на радиосигнал 10 ГГц. К нему добавляются 100 каналов с частотным разнесением поднесущих частот на 10 МГц при рабочей частоте первого канала 60 МГц. Эти каналы поднесущих смешиваются с гармоническим радиосигналом с несущей частотой 10 ГГц в гибридном ответвителе со сдвигом фазы в 90°. Непрерывное лазерное излучение с входной мощностью 10 дБм и длиной волны 1550 нм модулируется сформированным радиосигналом в оптическом LiNb модуляторе Маха-Цендера на LiNb-кристалле. Выходной сигнал модулятора передаётся по разным оптическим линиям связи в свободном пространстве протяжённостью 300 ... 1000 м под воздействием атмосферной турбулентности, определяемой структурной характеристикой флуктуаций показателя преломления. Система оценивается с точки зрения Q-добротности и частоты ошибок бит (BER) с использованием программного обеспечения Optisystem. Показано, что максимальная протяжённость связи при слабой турбулентности ($C_n^2 = 5 \times 10^{-15} \text{ м}^{-2/3}$) и $BER=10^{-9}$ составляет 950 м, а при сильной турбулентности ($C_n^2 = 5 \times 10^{-13} \text{ м}^{-2/3}$) – 850 м.

Радиосвязь; оптический канал; свободное пространство; поднесущие составляющие; мультиплексирование; амплитудная манипуляция; оптический модулятор Маха-Цендера; частоты ошибок бит; добротность.

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EVOLUTION OF RADIO OVER FREE SPACE OPTICAL COMMUNICATION UTILIZING SUBCARRIER MULTIPLEXING / AMPLITUDE SHIFT KEYING

The high demand for increased bandwidth, data rate and quality in optical communication systems in modern applications. Radio over free space optics (RoFSO) is deemed a new design methodology over wireless systems and networks. This technique has to ensure data rates like ones presented by means optical fiber communication techniques in keeping with a portion of its arrangement cost. Such systems are implemented by combined radio signal (RF) with optical signal, which containing various wireless administrations and Free Space Optics (FSO) link. In this paper, the simulation and evaluation system of Subcarrier Multiplexing/Amplitude Shift Keying (SCM/ASK) transmitter for Free Space Optical Communication is proposed. 1Gb/s data Rate given to the system. Whilst 10 GHz radio frequency signal setting in electrical amplitude modulator. Thereafter, radio signal is added with 100 subcarrier channels of 10 MHz spacing channel at operated first channel frequency of 60 MHz. These subcarrier channels with 90° combined with 10 GHz sin wave signal (radio frequency) at hybrid coupler, the combination of each subcarriers and radio signal are modulated by LiNb Mach-Zehnder optical modulator with 1550 nm wavelength continues wave laser signal at 10 dBm input power. The optical modulated signal (after optical modulator) is transmitted over a various free space optical link from 300m to 1km under the Atmospheric turbulence effect (the structure feature of the refractive index). The system is evaluated utilizing Opti system software with Q-factor and BER terminology. It is shown that the maximum optical distance for weak turbulence ($C_n^2 = 5 \times 10^{-15} \text{ m}^{-2/3}$) at BER equal to 10^{-9} is 950m, while the maximum optical distance for strong turbulence $C_n^2 = 5 \times 10^{-13} \text{ m}^{-2/3}$ is 850m.

Subcarrier Multiplexing; Radio Over Free Space Optics; Amplitude Shift Keying (ASK); Mach-Zehnder optical modulator; Radio Signal (RF); Q-factor, Bit Error Rate (BER).

Introduction. There have been many advantages of free space optical communication (FSO) systems or wireless optical communication, for instance large capacity, unlicensed system, excellent protection and minimal cost-efficiency of transmitting high data rates besides radio frequency (RF) signals with the identical size as optical fiber [1–6]. Though, it's a feasible technology that corresponding with point-to-point communication. FSO communication systems effectiveness is highly vulnerable to adverse atmospheric situations caused by fluctuations in the deflective index due to temperature inhomogeneities and changes in pressure.[4]. Due to variations in the refractive index via transmission signal along the path link, atmospheric turbulence affects variations (scintillation) in both the intensity and phase of the received signal [2].

Many different mathematical models have recently been suggested to explain this variation based on atmospheric turbulence in both weak and strong fading regimes in the optical channel, such as:

- 1) log-normal distribution;
- 2) gamma-gamma distribution;
- 3) negative exponential dissemination [4–7].

In addition, In addition, the analysis of the malfunction probability and the median capacity of free – space channels is evaluated, derived from the closed form expression for the malfunction probability and the regular capacity of communication systems over atmospheric turbulence-induced fading channels modelled by the distribution of log-normal and gamma-gamma with regard to turbulence influences [2]. It is proposed to simulate and compare the hybrid modulation technique namely PPM-MSK-SIM based on PPM and MSK subcarrier strength modulation. Additionally, theoretical analysis of the BER performance under lognormal turbulence model for an avalanche photodetector system [8].

In Conjunction with using the SIM-DPSK modulation method over the lognormal turbulence channel, the performance review of the free space optical communication system is proposed with regard to the misalignment effects. Likewise, the formulas for the average of BER and probability have been derived [9]. For the FSO framework with avalanche photodetector receiver, it is proposed to derive theoretical representation for the average BER of the SIM-BPSK modulation format.

In addition, under the influence of the gamma-gamma atmospheric turbulence model, the magnitude fluctuation of the optical signal is regarded [10]. The simulation studies of optical communications utilized subcarrier phase shift keying intensity modulation over atmospheric turbulence conditions. The bit error rate is derived for optical system using either on/off key or subcarrier PSK intensity modulation format [11].

In relation to our knowledge, a study of the optical communication method of radio over free space using subcarrier multiplexing / Amplitude Shift Keying was not carried out in previous papers. Therefore, the assessment of radio over free space optical (FSO) transmission at different free space links from 300 m to 1 km with 10 GHz radio signal is fulfilled in this paper. It is proposed to handle all this under atmospheric turbulences conditions (weak and strong) utilizing subcarrier multiplexer/Amplitude Shift Keying (SCM/ASK) is suggested. In addition, the method of estimation is explained in terms of the BER Q-factor and value.

Theoretical analysis. This section presents a brief overview of the Amplitude Shift Keying (ASK), optical subcarrier multiplexing (SCM), optical modulation and gamma-gamma distribution model turbulence.

A. Amplitude Shift Keying (ASK)

Amplitude shift keying is a type of amplitude modulation which characterizes the binary data (0 or 1) for differences within the amplitude of a carrier wave. Fig. 1. is represented the waveform of the amplitude shift keying (ASK) signal, the transmitted ASK signal for symbol i is defined by [12].

$$S_i(t) = \sqrt{\frac{2E_i(t)}{T}} \cos(\omega_o t + \phi) \quad \left\{ \begin{array}{l} 0 \leq t \leq T \\ i = 1, \dots, M \end{array} \right\}. \quad (1)$$

Where the amplitude phrase $\sqrt{2E_i(t)/T}$ will utilize M values, besides the phase term ϕ is a constant value.

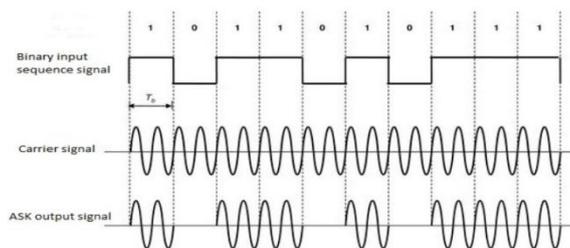


Fig. 1. Binary Amplitude Shift Keying (ASK)

B. Optical subcarrier multiplexing (SCM)

Optical subcarrier multiplexing (SCM) [13] is a system through it numerous signals are multiplexed in the radio frequencies domain as well as used to modulate with the light signal to be transferred through a single wavelength [14]. Furthermore, this system considers a more sensitive to noise effect and more flexible for superior data rate diffusion in the field of optical communication to increase the efficiency of the bandwidth [15]. The basic scheme of SCM is demonstrated in fig. 2.

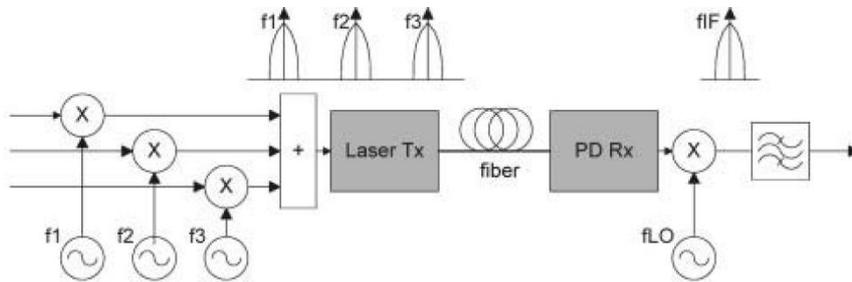


Fig. 2. The basic scheme of Subcarrier Multiplexing (SCM) within optical system [20]

C. Optical modulation

In optical communication systems, the electrical signal is modulated onto a light source (carrier) by an optical modulator. The configuration of Dual-Arm LiNb Mach-Zehnder optical Modulator is shown in fig. 3. The electric signal is divided into two signals V_1 and V_2 with 90° phase shifts between them, mathematical expression for each signal as given in Eq. (1).

$$V_1(t) = V_{RF} \cos(\omega_{RF}(t) + \phi(t)). \tag{2}$$

Where V_{RF} , $\omega_{RF}(t)$ and $\phi(t)$ correspond to the amplitude, frequency and phase of electrical signal component correspondingly, Whereas, the yield signal of dual-arm MZM which is define in Eq. (2) [16].

$$E_o = \frac{E_i}{2} \left[\exp\left(j\pi \frac{V_1}{V_\pi}\right) + \exp\left(j\pi \frac{V_2}{V_\pi}\right) \right]. \tag{3}$$

Where E_i is the light signal, V_1 and V_2 are the modulated electrical signals, V_π is the voltage to offer a phase shift to each phase modulator.

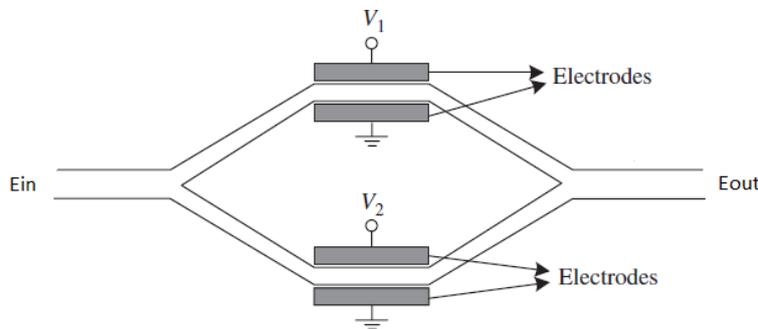


Fig. 3. The basic scheme Dual-Arm MZM [21]

D. Gamma-Gamma dissemination model turbulence

The gamma-gamma prototype is represent mutually small-scale in addition large-scale atmospheric fluctuations besides factor the irradiance such as the result of two separate random procedures, every getting a gamma PDF, as the expression following [4, 6, 17]:

$$f_I(I) = \frac{2(ab)^{(a+b)/2}}{\Gamma(a)\Gamma(b)} I^{\{(a+b)/2\}-1} K_{a-b}(2\sqrt{abI}). \tag{4}$$

Where $\Gamma(.)$ is the Gamma function, $K_n(.)$ is the modified Bessel function of the second kind of order n, a and b are the active numbers of small scale what is more large scale eddies of the scattering situation and characterized for spherical wave through aperture-averaged scintillation as following [4, 18, 19]

$$a = \left[\exp \left(\frac{0.49\delta^2}{(1 + 0.18d^2 + 0.56\delta^{12/5})^{7/6}} \right) - 1 \right]^{-1} \quad (5)$$

and

$$b = \left[\exp \left(\frac{0.51\delta^2}{(1 + 0.9d^2 + 0.62\delta^{12/5})^{5/6}} \right) - 1 \right]^{-1} \quad (6)$$

Where: $d = \sqrt{kD^2/4L}$, $k = 2\pi/\lambda$ is the optical wave number, L is the length of the optical link and D is the receiver's aperture diameter. The parameter δ^2 is the Rytov variance given by

$$\delta^2 = 1.23C_n^2 k^{7/6} L^{11/6}. \quad (7)$$

Through C_n^2 being the altitude-dependent turbulence strength and changing from 10^{-17} to $10^{-13} \text{ m}^{-2/3}$ matching to the atmospheric turbulence terms.

Simulation setup. The proposed system of radio over free space optical communication utilizing subcarrier multiplexing/Amplitude Shift Keying transmitter is illustrated in fig.4. This system is simulated using optisystem software. The design simulation as well as system factors are inserted in table 1 and table 2 respectively.

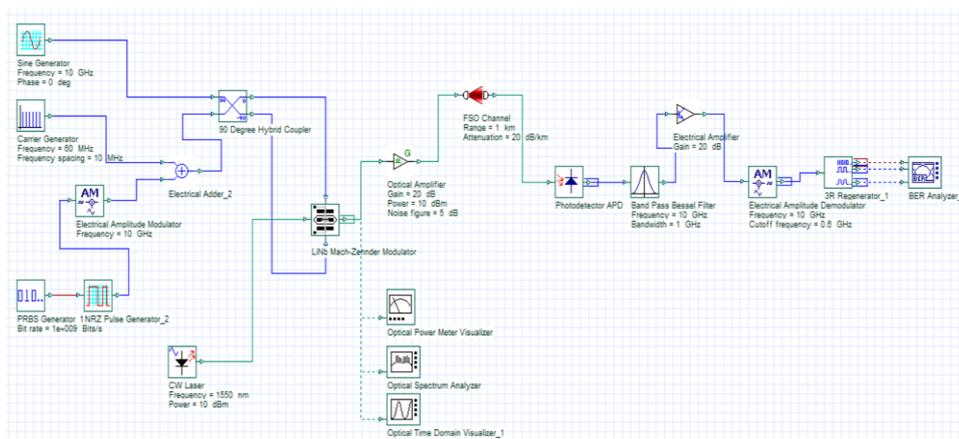


Fig. 4. Block diagram of proposed SCM/ASK free space optical communication system

Table 1

Layout simulation parameters

Parameters	Value
Bit rate G bit/s	1
Sequence length	64
Samples / bit	256
Central frequency (nm)	1550

Table 2

System parameters

Parameters	Value
ASK frequency GHz	10
Carrier generator frequency MHz	60
Sinewave generator frequency GHz	10
Optical amplifier gain dB	20
Optical amplifier power dBm	10
Optical amplifier noise figure dB	5
Free space channel attenuation dB/Km	20
APD photodiode responsivity A/W	0.9
APD photodiode dark current nA	10
Band pass Bessel filter frequency GHz	10
Bandwidth Bessel filter GHz	1
ASK demodulated frequency GHz	10
Low pass filter cutoff frequency GHz	0.6

A pseudo-random bit sequence (PRBS) initiator involves the transmitter and generates the modulation signal. The NRZ pulse generator has been utilized as low speed electrical coded. When setting the 10 GHz radio signal in the electric amplitude modulator as a baseband radio frequency converter. In this case, the frequency domain is given by the modulation format for amplitude shift keying (ASK). On the other hand, the radio frequency signal is modulated with subcarrier multiplexing, involving the setting of the carrier generator at 100 channels of the 10 MHz spacing channel at the 60 MHz first channel operated and the 10 GHz frequency of the sinewave signal generator. The 90° hybrid coupler is provided with these combined signals. A 90° hybrid coupler breaches the input signal into two output with 90° phase shift in the middle of each other. After that, the subcarrier radio signals of the hybrid coupler are came to the tow arm of LiNb Mach-Zehnder optical Modulator which modulate and adjust electrical signal to optical domain with continuous wave laser source has the yield power 10 dBm, linewidth of 10 MHz and 1550nm wavelength. In free space link, the transmitted signals are propagated over various lengths from 300m to 1km under different atmospheric turbulence conditions (gamma-gamma distribution model), weak ($C_n^2 = 5 \times 10^{-15} \text{ m}^{-2/3}$) and strong ($C_n^2 = 5 \times 10^{-13} \text{ m}^{-2/3}$). Signals are processed on the receiver side of the APD photodiode used to transform optical signal to electrical signal with a 5-degree receiver gain, 0.9 A / W responsivity and 10 nA dark current. Subsequently, the subcarrier radio signal is transmitted at 10 GHz frequency and 1 GHz bandwidth through the electric band pass Bessel filter configuration. Radio signal demodulated by AM electric demodulator set to 10 GHz frequency and 0.6 GHz cut-off frequency after filter.

Results. Effects are simulated using version 10 of Opti system software. The transmission optical spectrum after the LiNb Mach-Zehnder optical modulator is shown in fig. 5. The Q-factor values vs. transmission distance are shown in fig. 6 (free space link from 300m to 1km) according to various atmospheric turbulence conditions (feeble

turbulence at $C_n^2 = 5 \times 10^{-15} \text{ m}^{-2/3}$ and strong turbulence at $C_n^2 = 5 \times 10^{-13} \text{ m}^{-2/3}$). At the same conditions, fig. 7 shown the values of bit error rate (BER) vs transmission distance. The evaluation system is depending of the special value of BER equal to 10^{-9} .

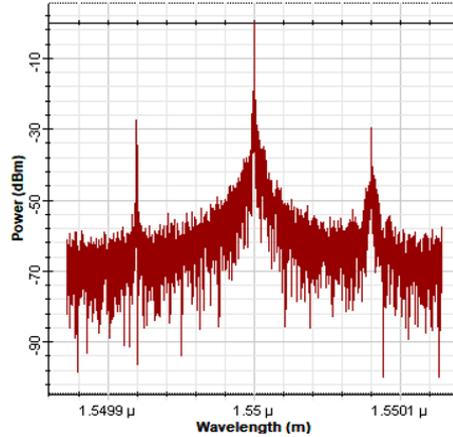


Fig. 5. optical spectrum at 1550nm wavelength after LiNb Mach-Zehnder optical Modulator

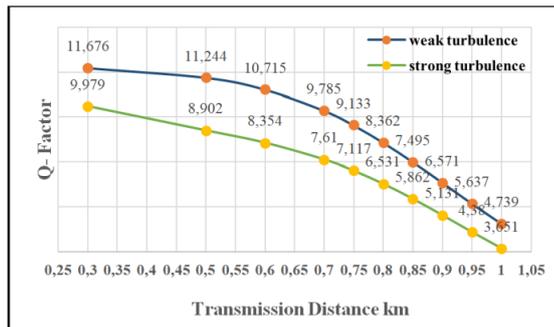


Fig. 6. Q-factor vs transmission distance for ($C_n^2 = 5 \times 10^{-15} \text{ m}^{-2/3}$) frail turbulence (Blue line) and $C_n^2 = 5 \times 10^{-13} \text{ m}^{-2/3}$ sturdy turbulence (Green line).

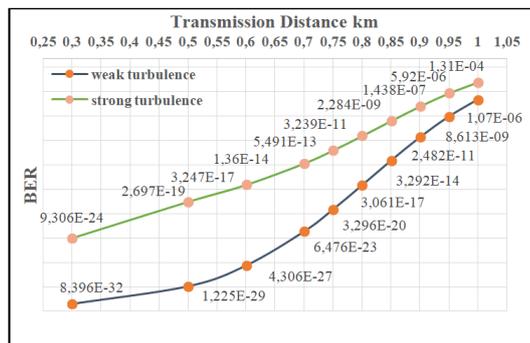


Fig. 7. BER vs transmission distance for ($C_n^2 = 5 \times 10^{-15} \text{ m}^{-2/3}$) frail turbulence (Blue line) and $C_n^2 = 5 \times 10^{-13} \text{ m}^{-2/3}$ sturdy turbulence (Green line)

Conclusion. We have proposed the subcarrier multiplexing/Amplitude Shift Keying transmitter system for radio over free space optical communication. Radio frequency, 10 GHz is modulated with the multiplexing portion of the subcarrier including the transporter generator and the sine wave signal. Free space optical channel under deferent atmospheric turbulence conditions weak and strong. The simulation system is reported that the maximum transmission distance for weak atmospheric turbulence is 950m at BER equal to 8.613×10^{-9} and Q-factor is 5.637. While the maximum transmission distance for strong atmospheric turbulence is 850m at BER equal to 2.284×10^{-9} and Q-factor is 5.862.

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