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RESEARCH ARTICLE

Performance Evaluation of SSK Modulation Over Shadowed-Rician Land Mobile Satellite Links

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ABSTRACT We investigate the performance of satellite communication systems acquiring the space shift keying (SSK) modulation technique over shadowed-rician (SR) land mobile satellite (LMS) link. Specifically, we discuss the analytical performance of the considered system over independent and identically distributed SR fading channels in terms of symbol error rate (SER), diversity order, and average capacity. The SER of the considered set-up is derived by utilizing moment generating function (MGF) expression over the SR fading LMS communication links. The analytical diversity order of the scheme is derived by using SER expression. We consider the effect of elevation angles on the SER performance, diversity order, and channel capacity of the considered SSK-assisted satellite communication system. As observed from simulation and analytical results, the performance of the considered set-up can be raised by improving elevation angles. Further, a closed-form expression of the average capacity of the SSK assisted satellite communication system is also derived. It is shown through simulation and analysis that the fading conditions and elevation angle does not affect the diversity order of the system, but it adversely acts on the SER performance and average capacity of the system.

INDEX TERMS Space shift keying (SSK), fading channels, land mobile satellite (LMS), multiple-input single-output (MISO).

I. INTRODUCTION

Satellite is now an integral component for upcoming generation of wireless communication system because it provides coverage over a very large area, used for broadcasting, disaster relief, and navigation. In addition, these systems have also been found very useful in providing such services in under-populated areas [1], [2], [3], [4], [5]. Multiple-input multiple-output (MIMO) antenna based techniques have been deployed in order to substantially improve the performance of satellite-based systems [6], [7]. However, most of the existing state-of-the-art works related to MIMO techniques focus over the downlink transmissions which assume the ideal feeder uplink [8], [9], [10]. It is shown in [11], [12], [13], [14], and [15] that the hybrid satellite-terrestrial systems are very useful to avoid masking effect and reduce latency. The performance of the AF based hybrid satellite-terrestrial system is presented in [12]. A method of beamforming and combining in hybrid satellite-terrestrial system is proposed in [13]. The high system capacity and energy efficiency of the multi-antenna technique for the applications of satellite communication is shown in [15]. Further, the concept of cognitive radio is also very useful in satellite communication systems. The outage performance of cognitive satellite terrestrial network is explored in [14] under interference-limited scenarios. In [5], the advantages of employing multiple antennas in cognitive satellite terrestrial networks is explored and also provide the exact and asymptotic outage probability with interference power constraint. The analysis of outage probability (OP) of hybrid satellite terrestrial networks is shown in [16], whereas [17] provides its average symbol error rate (ASER). The symbol error analysis of hybrid satellite-terrestrial cooperative networks with cochannel interference and in the presence of interference is given in [18]. The performance of multiuser hybrid satellite-terrestrial relay networks with opportunistic scheduling is discussed in [19]. A large MIMO satellite communication is proposed in [20]. A very accurate channel model for the land mobile satellite link is given

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in [21]. The distribution of the product of square shadowed-rician (SR) random variable is proposed in [22].

Spatial modulation (SM) exploits the index of transmitting antenna to improve the spectral efficiency of a wireless communication system. SM performs better when the channel gains are sufficiently different from each other. The SM technique is presented in [23] and [24] for RF multiple-input-multiple-output (MIMO) system. For generalized MIMO technology, the use of SM is proposed in [25]. Space shift keying (SSK) is discussed in [26] as a special case of the SM, where only antenna indices are used to transfer the information. Performance comparison of different spatial modulation schemes in correlated fading channels is studied in [27]. The space-time block coded modulation concept for MIMO systems is presented in [28] using spatial–constellation diagram. An improved version of space modulation schemes is proposed in [29] and [30]. It is shown in [30] that the proposed scheme in [30] can achieve a transmit–diversity gain. A general method for performance evaluation of SSK modulation for MISO correlated Nakagami-m fading channels is presented in [31]. A feedback based SSK modulation is proposed in [32]. The performance of a dual-hop DF-based LMS communication network is proposed in [33], where both the uplink and downlink of the two hops undergo SR distribution. An inclusive survey of LMS systems as well as services from various perspectives have been studied in [34]. In [35], the propagation problems of LMS communication links and the statistical resolutions is presented.

SSK exploits the difference between fading scenarios. Therefore, it is very useful for satellite communication systems, where there is a large possibility that channels fade differently. To the best of our knowledge, the performance of SSK assisted satellite communication system has not been discussed in the literature, so far. In this paper, we analyze the performance of SSK assisted satellite communication system in terms of SER, diversity order and ergodic capacity. We consider the i.i.d. SR land mobile satellite channels and derive a closed-form expression of moment generating function (MGF). Moreover the effect of elevation angle on the performance is also discussed. The proposed analysis demonstrates that the SER and capacity of the scheme can be improved by increasing the elevation angle of the satellite.

II. SYSTEM MODEL

A satellite MISO communication system with single receive antenna at the satellite and N transmit antennas at the earth station (ES) is considered. The transmission from ES to satellite, i.e. uplink transmission of the signal is considered. SSK modulation is used at the ES, in which information bits are mapped into the transmit antenna indexes. At a time of bit/symbol transmission, only one antenna is activated according to the information bit/symbol, all other antennas available at the ES are inactive. It is assumed that perfect channel state information (CSI) is available at the satellite. The received signal at the satellite can be written as

$$r = h_i + n, \tag{1}$$

where n represents the complex additive white Gaussian noise (AWGN) with zero mean and σ^2 variance, h_i is the channel between i-th antenna at the ES and the antenna placed at the satellite; i is the information bit/symbol transmitted from the ES. At the satellite, the antenna index needs to be detected. The detector of the symbol/bit can be derived by maximizing the conditional probability density function (PDF) of $r|h_i$. The PDF of $r|h_i$ can be written as

$$f_R(r|h_i) = \frac{1}{2\pi} e^{\left(-\frac{(r-h_i)^2}{2}\right)}, \tag{2}$$

where $e(.)$ denotes the exponential function. By taking the natural logarithm of the conditional p.d.f. of $r|h_i$, the decision metric at the satellite can be written as

$$\Lambda = \arg \min_{j} \left| r - h_j \right|^2, \tag{3}$$

where $j \in \{1, 2, 3 \ldots, i\}$. From (1) and (3), the instantaneous SNR at the satellite can be written as

$$\gamma_i = |h_i - h_j|^2 \bar{\gamma}, \tag{4}$$

where $\bar{\gamma} = 1/\sigma^2$ is the average SNR.

III. PERFORMANCE EVALUATION OF SSK ASSISTED SATELLITE COMMUNICATION SYSTEM OVER I.I.D SR FADING CHANNELS

Channel Model: We assume that the ES-satellite link is distributed as i.i.d. SR fading channel. It is shown in [21] that SR fading distribution very accurate fit for land mobile satellite links. The PDF of $|h_i|^2$ can be written with the help of [21], as

$$f_{|h_i|^2}(x) = \alpha_i e^{-\beta_i x} {}_1F_1(m_i; 1; \delta_i x), \quad x > 0, \tag{5}$$

where $\alpha_i = 0.5(2bm_i/(2bm_i + \Omega_i))^{m_i}/b$, $\beta_i = (0.5/b_i)$, $\delta_i = 0.5\Omega_i/(2b_i^2 m_i + b\Omega_i)$, the parameter Ω_i is the average power of line of sight (LOS) component of i-th channel, $2b_i$ denotes the average power of the multipath component, and $0 \leq m_i \leq \infty$ is the Nakagami parameter, and ${}_1F_1(a; b; z)$ is the confluent Hypergeometric function [[36], Eq. (9.210.1)].

It is demonstrated in [21] that a LMS channel model is valid for a wide range of elevation angles (ϕ). The dependence of LOS power, multipath power, and other parameters on the elevation angle ϕ is as follows:

$$\begin{aligned} b_i(\phi) = {} & -4.7943 \times 10^{-8} \times \phi^3 + 5.5784 \times 10^{-6} \times \phi^2 \\ & - 2.1344 \times 10^{-4} \times \phi + 3.2710 \times 10^{-2}, \end{aligned} \tag{6}$$

$$\begin{aligned} m_i(\phi) = {} & 6.3739 \times 10^{-5} \times \phi^3 + 5.8533 \times 10^{-4} \times \phi^2 \\ & - 1.5973 \times 10^{-1} \times \phi + 3.5156, \end{aligned} \tag{7}$$

and

$$\begin{aligned} \Omega_i(\phi) = {} & 1.4428 \times 10^{-5} \times \phi^3 - 2.3798 \times 10^{-3} \times \phi^2 \\ & + 1.2702 \times 10^{-1} \times \phi - 1.4864. \end{aligned} \tag{8}$$

A. MGF CALCULATION

Using standard definition, we can write the MGF of γ_i conditioned on the joint PDF of envelopes of the channels h_i and h_j, as

$$M_{\gamma_i}(s) = E_{|h_i|,|h_j|} \left[e^{-s\gamma_i} \right]. \tag{9}$$

From (4) and (9), the MGF can be written as

$$M_{\gamma_i}(s) = E_{|h_i|,|h_j|} \left[e^{-s|h_i - h_j|^2 \bar{\gamma}} \right]. \tag{10}$$

In order to solve the MGF expression given in (10), we need the PDF of the envelopes of the channels. Further, by following the steps given in [[31], section III A-2], the MGF conditioned on $|h_i|$ and $\left|h_j\right|$ can be obtained as

$$M_{\gamma_i}(s|\,|h_i|\,,\left|h_j\right|) = e^{-s|h_i|^2\bar{\gamma}} e^{-s\left|h_j\right|^2\bar{\gamma}} I_0(2sxy\bar{\gamma}), \tag{11}$$

where $I_0(.)$ denotes the modified Bessel function of zero order. The PDF of $|h_i|$ can be written by using [[37], Eq. (10)] as

$$f_{|h_i|}(u) = 2u\alpha_i e^{-\beta_i u^2} {}_1F_1(m_i;\, 1;\, \delta_i u^2), \quad u > 0, \tag{12}$$

By doing averaging of (10) over joint PDF of $|h_i|\,, |h_i|$, the MGF can be written as

$$M_{\gamma_i}(s|x, y) = \int_0^\infty \int_0^\infty e^{-sx^2\bar{\gamma}} e^{-sy^2\bar{\gamma}} \times I_0(2sxy\bar{\gamma}) f_{|h_i|,\left|h_j\right|}(x, y)dxdy. \tag{13}$$

From (11) and (12), we obtain

$$M_{\gamma_i}(s|y) = e^{-sy^2\bar{\gamma}} \int_0^\infty e^{-sx^2\bar{\gamma}} I_0(2sxy\bar{\gamma}) \times \left(2x\alpha_i e^{-\beta_i x^2} {}_1F_1(m_i;\, 1;\, \delta_i x^2)\right) dx. \tag{14}$$

By using the series expression of ${}_1F_1(.;\, .;\, .)$ in (14), we get

$$M_{\gamma_i}(s|y) = e^{-sy^2\bar{\gamma}} \sum_{k=0}^{\infty} \frac{(m_i)_k \delta_i^k}{(1)_k k!} \int_0^\infty e^{-sx^2\bar{\gamma}} I_0(2sxy\bar{\gamma}) \times 2x\alpha_i e^{-\beta_i x^2} x^{2k} dx, \tag{15}$$

where $(a)_0 = 1$, and $(a)_k$ is the Pochhammer symbol. By substituting $x^2 = t$ in (15), we obtain

$$M_{\gamma_i}(s|y) = \alpha_i e^{-sy^2\bar{\gamma}} \sum_{k=0}^{\infty} \frac{(m_i)_k \delta_i^k}{(1)_k k!} \times \int_0^\infty t^k e^{-(s\bar{\gamma}+\beta_i)t} I_0(2sy\bar{\gamma}\sqrt{t})dt, \tag{16}$$

In order to solve the integral, given in (15), we write the exponential function and modified bessel function in terms of Meijer G function. Following conversions are used [38]:

$$e^{-(s\bar{\gamma}+\beta_i)t} = G_{01}^{10}\left((s\bar{\gamma}+\beta_i)t \,\middle|\, \begin{matrix} \cdot \\ 0 \end{matrix}\right) \tag{17}$$

and

$$I_0(2sy\bar{\gamma}\sqrt{t}) = G_{02}^{10}\left(-s^2\bar{\gamma}^2 y^2 t \,\middle|\, \begin{matrix} \cdot \\ 0, 0 \end{matrix}\right). \tag{18}$$

After substituting the values of $e^{-(s\bar{\gamma}+\beta_i)t}$ and $I_0(2sy\bar{\gamma}\sqrt{t})$ in (16), we get

$$M_{\gamma_i}(s|y) = \alpha_i e^{-sy^2\bar{\gamma}} \sum_{k=0}^{\infty} \frac{(m_i)_k \delta_i^k}{(1)_k k!} \times \int_0^\infty t^k G_{01}^{10}\left((s\bar{\gamma}+\beta_i)t \,\middle|\, \begin{matrix} \cdot \\ 0 \end{matrix}\right) G_{02}^{10}\left(-s^2\bar{\gamma}^2 y^2 t \,\middle|\, \begin{matrix} \cdot \\ 0, 0 \end{matrix}\right) dt \tag{19}$$

With the help of [[38], Eq. (21)], the integral given in (19) can be solved as

$$M_{\gamma_i}(s|y) = \alpha_i e^{-sy^2\bar{\gamma}} \sum_{k=0}^{\infty} \frac{(m_i)_k \delta_i^k}{(1)_k k!} \times (s\bar{\gamma}+\beta_i)^{-(k+1)} G_{12}^{11}\left(\frac{-s^2\bar{\gamma}^2 y^2}{s\bar{\gamma}+\beta_i} \,\middle|\, \begin{matrix} -k \\ 0, 0 \end{matrix}\right) dt. \tag{20}$$

Further, by averaging the expression of $M_{\gamma_i}(s|y)$ over $f_Y(y)$, we get

$$M_{\gamma_i}(s) = \alpha_i \sum_{k=0}^{\infty} \frac{(m_i)_k \delta_i^k}{(1)_k k!} (s\bar{\gamma}+\beta_i)^{-(k+1)} \int_0^\infty e^{-sy^2\bar{\gamma}} \times G_{12}^{11}\left(\frac{-s^2\bar{\gamma}^2 y^2}{s\bar{\gamma}+\beta_i} \,\middle|\, \begin{matrix} -k \\ 0, 0 \end{matrix}\right) \left(2y\alpha_j e^{-\beta_j y^2} {}_1F_1(m_j;\, 1;\, \delta_j y^2)\right) dy. \tag{21}$$

Again by using the series expression of ${}_1F_1(.;\, .;\, .)$ and then converting the exponential function in terms of Meijer-G function, we get

$$M_{\gamma_i}(s) = \alpha_i\alpha_j \sum_{k=0}^{\infty} \frac{(m_i)_k \delta_i^k}{(1)_k k!} \sum_{p=0}^{\infty} \frac{(m_j)_p \delta_j^p}{(1)_p p!} (s\bar{\gamma}+\beta_i)^{-(k+1)} \times \int_0^\infty G_{01}^{10}\left((s\bar{\gamma}+\beta_j)y^2 \,\middle|\, \begin{matrix} \cdot \\ 0 \end{matrix}\right) G_{12}^{11}\left(\frac{-s^2\bar{\gamma}^2 y^2}{s\bar{\gamma}+\beta_i} \,\middle|\, \begin{matrix} -k \\ 0, 0 \end{matrix}\right) y^{2p} 2y dy. \tag{22}$$

By substituting $\bar{\gamma}y^2 = t$ and with the help of [[38], Eq. (21)], the MGF expression given in (21) can be obtained in closed-form as

$$M_{\gamma_i}(s) = \alpha_i\alpha_j \sum_{k=0}^{\infty} \frac{(m_i)_k \delta_i^k}{(1)_k k!} \sum_{p=0}^{\infty} \frac{(m_j)_p \delta_j^p}{(1)_p p!} (s\bar{\gamma}+\beta_i)^{-(k+1)} \times (s\bar{\gamma}+\beta_j)^{-(p+1)} G_{22}^{12}\left(\frac{-s^2\bar{\gamma}^2}{(s\bar{\gamma}+\beta_i)(s\bar{\gamma}+\beta_j)} \,\middle|\, \begin{matrix} -k, -p \\ 0, 0 \end{matrix}\right). \tag{23}$$

B. SER CALCULATION

The exact SER for the SSK assisted satellite communication system can be obtained by using [[39], Eq. (4)]. But it can be observed from (23) that the MGF expression consists Meijer-G functions, therefore, the integral obtained from [[39], Eq. (4)] and (23) is very difficult to solve. To avoid this complexity, we use approximate expression of the SER [[39], Eq. (9)]. Moreover, it is demonstrated in [[39], Eq. (9)], that this approximation fits very accurately for all values of M. The SER of the considered set-up for M-PSK constellation can be obtained with the help of (22) and the relation given by [[39], Eq. (9)], as

$$P_{MPSK} \approx \sum_{h=1}^{3} \nu_h M_{\gamma_i}(\zeta_h)\,, \tag{24}$$

where $\nu_1 = \theta/(2\pi) - 1/6$, $\nu_2 = 1/4$, $\nu_3 = \theta/(2\pi) - 1/4$, $\zeta_1 = g_{MPSK}$, $\zeta_2 = 4g_{MPSK}/3$, $\zeta_3 = g_{MPSK}/sin^2(\theta)$, $g_{MPSK} = sin^2(\pi/M)$, and $\theta = (M-1)\pi/M$.

By using (23) and (24), the approximate SER of the considered set-up can be written in the closed-form as

$$P_{MPSK} \approx \sum_{h=1}^{3} \nu_h \Bigg(\alpha_i \alpha_j \sum_{k=0}^{\infty} \frac{(m_i)_k \delta_i^k}{(1)_k k!} \sum_{p=0}^{\infty} \frac{(m_j)_p \delta_j^p}{(1)_p p!} \\ \times (\zeta_h \bar{\gamma} + \beta_i)^{-(k+1)} (\zeta_h \bar{\gamma} + \beta_j)^{-(p+1)} \\ \times G_{22}^{12} \Bigg(\frac{-\zeta_h^2 \bar{\gamma}^2}{(\zeta_h \bar{\gamma} + \beta_i)(\zeta_h \bar{\gamma} + \beta_j)} \Bigg| \begin{matrix} -k, -p \\ 0, 0 \end{matrix} \Bigg) \Bigg). \tag{25}$$

C. DIVERSITY ORDER

Diversity order is used to know the behavior of the system at very high values of SNR. Following conversion is used for calculating the analytical diversity of the considered system:

$$ {}_2F_1(a, b; c; -x) = \frac{\Gamma(c)}{\Gamma(a)\Gamma(b)} G_{22}^{12} \left(x \middle| \begin{matrix} 1-a, 1-b \\ 0, 1-c \end{matrix} \right), \tag{26}$$

where ${}_2F_1(a, b; c; -x)$ is gauss hypergeometric function [36], [40]. From (25) and (26), we get

$$P_{MPSK} \\ \approx \sum_{h=1}^{3} \nu_h \Bigg(\alpha_i \alpha_j \sum_{k=0}^{\infty} \frac{(m_i)_k \delta_i^k}{(1)_k k!} \sum_{p=0}^{\infty} \frac{(m_j)_p \delta_j^p}{(1)_p p!} \\ \times (\zeta_h \bar{\gamma} + \beta_i)^{-(k+1)} (\zeta_h \bar{\gamma} + \beta_j)^{-(p+1)} \Gamma(k+1) \Gamma(p+1) \\ \times {}_2F_1(k+1, p+1; 1; \frac{\zeta_h^2 \bar{\gamma}^2}{(\zeta_h \bar{\gamma} + \beta_i)(\zeta_h \bar{\gamma} + \beta_j)}). \tag{27}$$

By substituting $k = p = 0$ in (27) for calculating the diversity order, we get

$$P_{MPSK} \approx \sum_{h=1}^{3} \nu_h \alpha_i \alpha_j (\zeta_h \bar{\gamma} + \beta_i)^{-1} (\zeta_h \bar{\gamma} + \beta_j)^{-1} \\ \times {}_2F_1(1, 1; 1; \frac{\zeta_h^2 \bar{\gamma}^2}{(\zeta_h \bar{\gamma} + \beta_i)(\zeta_h \bar{\gamma} + \beta_j)}). \tag{28}$$

It is given in [40] that ${}_2F_1\ (a, b; b; z) = (1-z)^{-a}$ for all values of b. By using this relation in (28) and after some algebra, we get

$$P_{MPSK} \approx \sum_{h=1}^{3} \frac{\nu_h \alpha_i \alpha_j}{\zeta_h \bar{\gamma}\ (\beta_i + \beta_j) + \beta_i \beta_j}. \tag{29}$$

It can be observed from (29) that the diversity order of the considered satellite communication system is one.

D. ERGODIC CAPACITY

The average capacity of the SSK assisted satellite communication system can be derived using [41, Eq. (10)], as

$$C_{avg} = \frac{W}{\ln 2} \sum_{n=1}^{T} \nu_n C_1(s_n) \left\{ \frac{\delta}{\delta s} M_{\gamma_i}(s) \bigg|_{s \to s_n} \right\}, \tag{30}$$

where W denotes the bandwidth. Eq. (29) converges rapidly and steadily which requires only few terms for accuracy in result, where the coefficients s_n and v_n are defined as

$$s_n = \tan \left(\frac{\pi}{4} \cos \left(\frac{2n-1}{2T} \pi \right) + \frac{\pi}{4} \right), \tag{31}$$

$$v_n = \frac{\pi^2 \sin \left(\frac{2n-1}{2T} \pi \right)}{4T \cos^2 \left(\frac{\pi}{4} \cos \left(\frac{2n-1}{2T} \pi \right) + \frac{\pi}{4} \right)}, \tag{32}$$

Where the truncation index T could be chosen as $T = 100$ to get a high level of accuracy.

$$C_1(s_n) = -H_{3,2}^{1,2} \left[\frac{1}{s_n} \middle| \begin{matrix} (1,1), (1,1), (1,1) \\ (1,1), (0,1) \end{matrix} \right], \tag{33}$$

where $H_{3,2}^{1,2}[\cdot]$ dentoes the Fox's H function [42] and $T \in Z+$, here $Z+$ is a positive integer. It can be observed from (33) that the average capacity can be derived by using the expression of MGF. From (23) and (35), we get

$$C_{avg} \\ = \frac{B}{\ln 2} \sum_{n=1}^{T} \nu_n C_1(s_n) \alpha_i \alpha_j \sum_{k=0}^{\infty} \frac{(m_i)_k \delta_i^k}{(1)_k k!} \sum_{p=0}^{\infty} \frac{(m_j)_p \delta_j^p}{(1)_p p!} \\ \times \left\{ \frac{\delta}{\delta s} (s\bar{\gamma} + \beta_i)^{-(k+1)} (s\bar{\gamma} + \beta_j)^{-(p+1)} \Gamma(k+1) \right. \\ \left. \times \Gamma(p+1) {}_2F_1 \left(k+1, p+1; 1; \frac{s^2 \bar{\gamma}^2}{(s\bar{\gamma} + \beta_i)(s\bar{\gamma} + \beta_j)} \right) \right. . \tag{34}$$

By using differentiation property of Gauss hypergeometric function, i.e., $\frac{d^n}{dz^n} {}_2F_1(a, b; c; z) = \frac{(a)_n (b)_n}{(c)_n} {}_2F_1(a+n, b+n; c+n; z)$ in (34), we obtain

$$C_{avg} \\ = \frac{B}{\ln 2} \sum_{n=1}^{T} \nu_n C_1(s_n) \alpha_i \alpha_j \sum_{k=0}^{\infty} \frac{(m_i)_k \delta_i^k}{(1)_k k!} \sum_{p=0}^{\infty} \frac{(m_j)_p \delta_j^p}{(1)_p p!} \\ \times \Gamma(k+1) \Gamma(p+1) \\ \times \Bigg[{}_2F_1 \left(k+1, p+1; 1; \frac{s^2 \bar{\gamma}^2}{(s\bar{\gamma} + \beta_i)(s\bar{\gamma} + \beta_j)} \right) \\ \times \Bigg(-\bar{\gamma}(p+1)(s\bar{\gamma} + \beta_i)^{-(k+1)} (s\bar{\gamma} + \beta_j)^{-(p+2)} \\ -\bar{\gamma}(k+1)(s\bar{\gamma} + \beta_j)^{-(p+1)} (s\bar{\gamma} + \beta_i)^{-(k+2)} \Bigg) \Bigg) \\ + (s\bar{\gamma} + \beta_i)^{-(k+1)} (s\bar{\gamma} + \beta_j)^{-(p+1)} \\ \times (k+1)_1 (p+1)_1 {}_2F_1 \\ \times \left(k+2, p+2; 2; \frac{s^2 \bar{\gamma}^2}{(s\bar{\gamma} + \beta_i)(s\bar{\gamma} + \beta_j)} \right) \\ \times \left(\frac{s^2 \bar{\gamma}^2}{(s\bar{\gamma}+\beta_i)(s\bar{\gamma}+\beta_j)} \left(\frac{2}{s} - \frac{\bar{\gamma}}{(s\bar{\gamma}+\beta_i)} - \frac{\bar{\gamma}}{(s\bar{\gamma}+\beta_j)} \right) \right) \Bigg]. \tag{35}$$

IV. NUMERICAL RESULTS

An SSK assisted satellite communication system is considered in which ES is equipped with two antennas and satellite consists single antenna.The satellite links are assumed to follow SR fading under different fading scenarios, i.e., Infrequent light shadowing (ILS) ($b = 0.158$, $m = 19.4$, and $\Omega = 1.29$), Average shadowing (AS) ($b = 0.126$, $m = 10.1$, and 0.835), and Frequent heavy shadowing (FHS) ($b = 0.063$, $m = 0.739$, and $\Omega = 8.97 \times 10^{-4}$) [21]

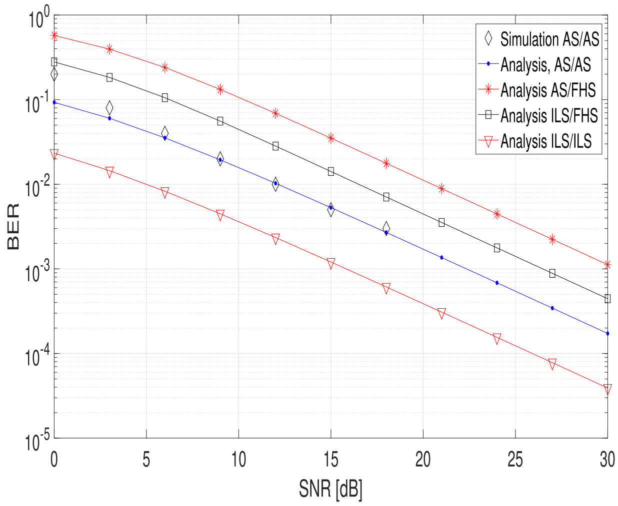

FIGURE 1. **Analytical and simulated plots of SNR versus BER under FHS, AS, and ILS scenarios.**

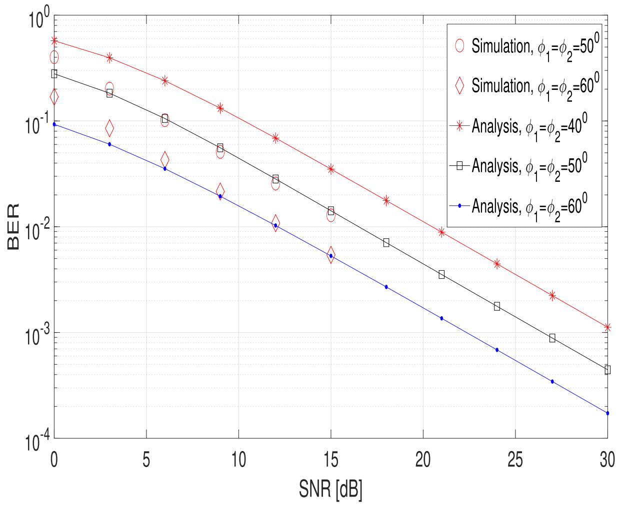

FIGURE 2. **Analytical and simulated plots of SNR versus BER with different elevation angles.**

for obtaining simulation and analytical results. Fig. 1 shows the BER versus SNR plots for AS/AS, ILS/ILS, AS/FHS, and ILS/FHS environment. Here AS/FHS means that first link undergoes the AS and second satellite link experiences FHS environment. It can be observed from Fig. 1. that the performance of ILS/ILS is the best among all set-ups because of the light shadowing. The performance of ILS/FHS is better than AS/FHS as seen from Fig. 1 because of the fact that the links are more separable from each other due to the quite different fading scenarios. Moreover, a closed match can be noticed from Fig. 1 between analytical and simulated results, which shows the correctness of the derived expressions.

Fig. 2 shows the plot of the simulated and analytical BER versus SNR plots of the SSK assisted satellite communication system with different elevation angles, i.e. for $\phi_1 = 40^0, 50^0, 60^0$ and $\phi_2 = 40^0, 50^0, 60^0$ $N = 2$, and with BPSK constellation. A closed match between simulated and analytical results can be observed from Fig. 2. With increasing values of ϕ_1 and ϕ_2, the performance of the considered system improves, as seen from Fig. 2. For example, the performance gain of approximately 3 dB can be obtained by improving elevation angle from 40^0 to 50^0 at BER=10^{-3}.

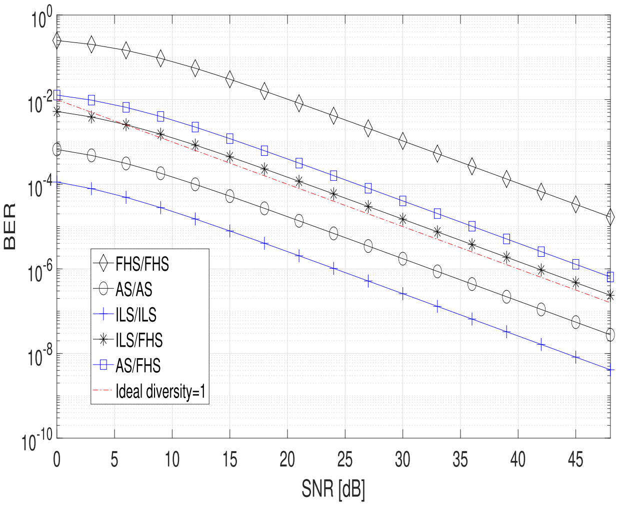

FIGURE 3. **Analytical plots of diversity order under FHS, AS, and ILS scenarios.**

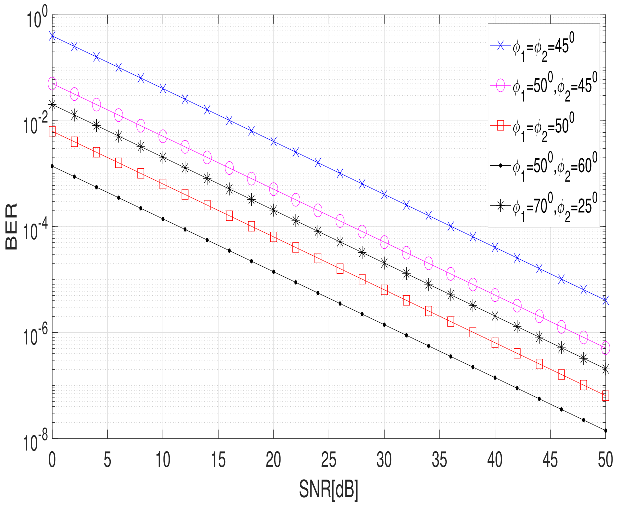

FIGURE 4. **Analytical plots of diversity order with different elevation angles.**

The diversity gain of the considered system under different fading scenarios is shown in Fig. 3, for i.i.d. SR fading and with BPSK constellation and $N = 2$. It can be observed from Fig. 3 that the fading does not affect the diversity order of the system. Moreover, a plot of ideal diversity of one is also shown in Fig. 3. The diversity order of the considered SSK assisted satellite communication system is one, as seen from Fig. 3. Further, it can also be noticed from Fig. 3 that if one link experiences the heavy shadowing, the performance deteriorates significantly. It can also be seen from Fig. 3 that if the satellite links undergo very different fading environment line one link is experiencing FHS and other is experiencing ILS, then the performance of the considered system improves because of SSK modulation technique.

Fig. 4 shows the analytical diversity order of the considered system with diffent values of elevation angles, i.e.,

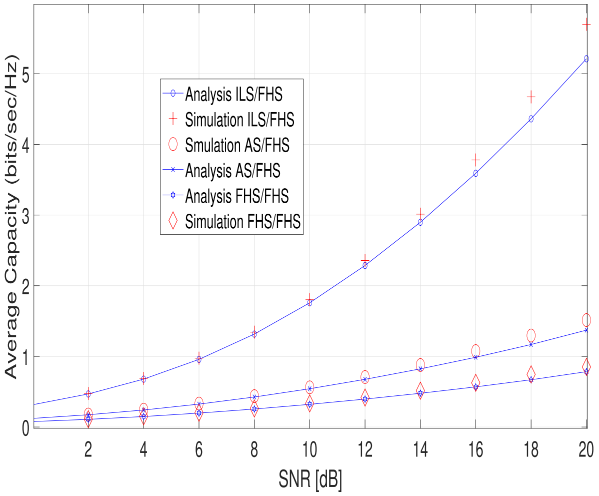

FIGURE 5. **Simulated and Analytical plots of average capacity with FHS, AS, and ILS scenarios.**

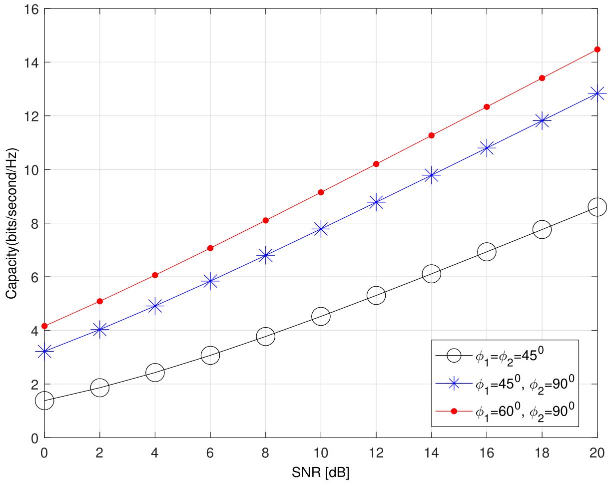

FIGURE 6. **Simulated and Analytical plots of average capacity with different elevation angles.**

$\phi_1 = 45^0, 50^0, 70^0$ and $\phi_2 = 25^0, 45^0, 50^0, 60^0$. The analytical results are generated by using (6-8) and (28).

It can be observed from Fig. 4 there is no effect of elevation angle on the diversity order of the considered system.

The average capacity (in bits/second/Hz) of the SSK assisted satellite communication system with FHS/FHS, AS/FHS, and ILS/FHS is shown in Fig. 5 over i.i.d. SR fading channels.

We have taken $T = 100$ in the derived average capacity expression (34). A close match can be observed between analytical and simulated results for all considered cases from Fig. 5. The lowest capacity is achieved by the considered system in the case of FHS/FHS, as seen from Fig. 5. If any one link undergoes different fading environment, then the capacity of the system improves. For example, an improvement of approximately 4.4 bits/sec/Hz in average capacity is observed from Fig. 5 when FHS/FHS environment changes to ILS/FHS environment.

The average capacity of the considered satellite communication system with different values of elevation angle, i.e., $\phi_1 = 45^0, 60^0$ and $\phi_2 = 45^0, 90^0$ is shown in Fig. 6. It can be perceived from the Fig. 6 that the average capacity of the considered system is improved by increasing the value of elevation angle. Further, if the elevation angle of two links is different from each other, the capacity of the system improves, as seen from Fig. 6.

V. CONCLUSION

In this paper, we have investigated the performance of SSK assisted satellite communication system over i.i.d. SR fading channels. The evaluation of analytical performance is done by using the closed-form expression of MGF, SER, diversity order, and average capacity of the considered setup. The impact of elevation angle on the performance of the considered system is also presented. It can be perceived through simulation and analytical results that elevation angle does not have any effect on the diversity order of the considered system. For different fading scenarios, the performance of the considered system changes remarkably. An important conclusion of this paper is that different fading for different antennas is beneficial from the performance perspective. It is very useful aspect in case of satellite communication, where the received power of the signal is very low. Only by geographical arrangement of the antennas at the ground, the performance of the satellite communication system can be improved.

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