IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received February 6, 2019, accepted March 7, 2019, date of publication March 14, 2019, date of current version April 1, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2905129

Impact of Hardware Impairments on Outage Performance of Hybrid Satellite-Terrestrial Relay Systems

HANG WU[1,2], **YULONG ZOU**[1,2], **(Senior Member, IEEE), WEIFENG CAO**[1,2], **ZHONG CHEN**[1,2], **THEODOROS A. TSIFTSIS**[3], **(Senior Member, IEEE), MANAV R. BHATNAGAR**[4], **(Senior Member, IEEE), AND RODRIGO C. DE LAMARE**[5,6], **(Senior Member, IEEE)**

[1]State Key Laboratory of Complex Electromagnetic Environmental Effects on Electronics and Information System, Luoyang, China
[2]School of Telecommunications and Information Engineering, Nanjing University of Posts and Telecommunications, Nanjing, China
[3]School of Intelligence Science and Engineering, Jinan University, Zhuhai, China
[4]Department of Electrical Engineering, IIT Delhi, New Delhi, India
[5]CETUC, PUC-Rio, Rio de Janeiro, Brazil
[6]Communications Research Group, Department of Electronics, University of York, York, U.K.

Corresponding author: Yulong Zou (yulong.zou@njupt.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 61671253 and Grant 91738201, in part by the Natural Science Foundation of Jiangsu Province under Grant BK20150040 and Grant BK20171446, and in part by the Open Project of the State Key Laboratory of Complex Electromagnetic Environmental Effects on Electronics and Information System under Grant BK218002.

ABSTRACT The hardware impairments of transceiver nodes that generate signal distortions degrade the reliability performance of communication systems. This paper investigates the impact of hardware imperfections on the outage performance of hybrid satellite-terrestrial relay systems (HSTRS), where a geosynchronous earth orbit (GEO) satellite transmits its data to the terrestrial destination with the help of decode-and-forward (DF) terrestrial relays. We consider that all network nodes are subjected to hardware impairments and propose a multi-relay selection (MRS) scheme to enhance the outage performance of the HSTRS. The traditional single-relay selection (SRS) scheme is also considered for comparison purposes. We derive closed-form outage probability expressions for both the SRS and MRS schemes. Moreover, an asymptotic outage probability analysis is carried for both the SRS and MRS schemes in the high signal-to-noise-ratio (SNR) region. The simulation results show that the outage performance of the HSTRS can be enhanced under the MRS scheme with a certain level of hardware impairments at the HSTRS. Compared to the condition of ideal hardware, the outage probability of HSTRS increases for both the SRS and MRS schemes if the hardware is not ideal. When the amplify-and-forward (AF) protocol is employed at relays, the outage performance of HSTRS degrades compared to that of DF for both the SRS and MRS schemes.

INDEX TERMS Hardware impairments, relay selection, hybrid satellite-terrestrial relay systems, outage probability.

I. INTRODUCTION

Recently, satellite communication systems have received considerable attention from the research community and are widely utilized in the field of navigation and broadcasting for its broad coverage to terrestrial users (see e.g., [1]–[3] and the references therein). Such systems are mainly impaired by the masking effect since obstacles between satellite and terrestrial users limit the transmission of the line of sight (LoS) link between source and a terrestrial destination. The effect caused by obstacles becomes even worse when the angles of satellite elevation are low or the terrestrial user is not outdoor. To decrease the masking effect, the hybrid satellite-terrestrial relay system (HSTRS) has been proposed in [1] by exploiting relaying techniques to enhance coverage and reliability.

Presently, the HSTRS has been studied extensively in existing technical literature. For example, in [4]–[6], the performance of HSTRS using amplify-and-forward (AF) relaying has been investigated. By contrast, the decode-and-forward (DF) relaying based on HSTRS has been

The associate editor coordinating the review of this manuscript and approving it for publication was Li Wang.

considered in [7] and [8]. The authors explored the situation of beamforming and combining at an AF HSTRS in [9]. Bhatnagar and Arti [10] studied the average symbol error rate (SER) of an HSTRS. An *et al.* [11] have investigated the secrecy capacity of a multi-antenna AF HSTRS based on the study of physical-layer security, which has been viewed as a potential paradigm of the satellite communication security by exploiting the physical characteristics of the wireless channel [12].

Propagation conditions in wireless communications are not always ideal. Arti [13] investigated the average rate of symbol error based on AF relaying of HSTRS under the condition of imperfect channel gains. Upadhyay and Sharma [14] considered the HSTRS which employs opportunistic user scheduling with feedback latency and co-channel interference. Guo *et al.* [15] studied the effect of the hardware impairments and interference on the land mobile satellite (LMS) system where a multi antenna satellite is utilized to act as a DF relay node. Also, Devendra and Prabhat [16] explored the effect of channel estimation errors on two-way relay multiple-input multiple-output (MIMO) systems under Rayleigh fading channels. In [17], the impact of imperfect channel estimation on cooperative diversity networks over Rician fading channels has also been investigated. In [18], the differential modulation were employed at two earth stations to eliminate the condition of channel estimation in a two-way satellite relaying (TWSR) system. Arti [19] also proposed a training protocol for a TWSR system to limit the effect of channel state information (CSI) estimation on the system. Guo *et al.* [20] explored the effect of hardware impairments on a TWSR system. The author considered the condition when the channel gains are unknown at AF HSTRS and proposed a scheme for link estimation and detection to reduce the average SER in [21].

Nevertheless, most of the aforementioned research efforts were devoted to exploring the HSTRS from different perspective under the condition of ideal hardware. In [15], the impact of hardware impairments on the outage performance of source-destination transmissions with the aid of a geostationary orbit regenerative satellite acting as a relay was studied. Unlike from the single satellite relay system of [15], we are motivated to investigate the outage performance of multiple relays assisted satellite communications in the presence of hardware impairments. The hardware impairments are often encountered in satellite communication systems. In practice, hardware subjects to the following impairments: phase noise I/Q imbalance and high power amplifier nonlinearities [22]–[24]. Bjornson *et al.* [25] first proposed a hardware impairment model and analyzed the impairment effect for dual-hop relaying networks. In [26], the effect of impaired hardware on MIMO systems was analyzed in terms of ergodic capacity. The authors also examined the performance of a single-hop network under the condition of impaired hardware in [27]. The authors analyzed the reliability of AF cooperative wireless networks with relay selection against impaired hardware [28]. In [29], the outage performance of cooperative cellular networks with impaired hardware was investigated. In [30], the reliability performance of multi-relay networks with impaired hardware was studied over Shadowed-Rician channels. In [31], the outage probability of a cognitive hybrid satellite-terrestrial network (CSTRN) with hardware impairments was investigated. Also, the joint effect of hardware impairments and channel estimation errors on the performance of CSTRN was studied in [32]. Guo *et al.* [33] derived closed-form outage probability expressions of a AF two-way multi-antenna multi-relay network when hardware impairments exist.

Hardware impairments deteriorate the performance of communication systems, so it is necessary to reduce its negative effects. As far as we know, few papers have paid attention to the exploration of the outage performance of multi-relay selection (MRS) scheme for HSTRS when hardware impairments exist. Clarke and de Lamare [34] optimized the joint transmit diversity of DF multi-relay cooperative MIMO systems, where these relays which can decode the source signal successfully forward their decoded outcomes. Ding *et al.* [35] studied the mean squared error (MSE) of AF multi-relay MIMO systems, where a certain number of antenna pairs in the MIMO relays are selected to forward the source signal. Zou *et al.* [36] first proposed the MRS scheme and analyzed the security versus reliability performance of the MRS scheme for cognitive radio networks. Moreover, Zhu *et al.* [37] investigated the security-reliability tradeoff of MRS scheme for multiple relays aided DF cooperation systems over Rayleigh fading channels.

In this work, we investigate the impact of hardware imperfections on the outage performance of HSTRS, where the satellite transmits its data to terrestrial destination with the help of DF terrestrial relays. The closed-form expression of outage probability for the MRS scheme is obtained. Simulation results show that the outage performance of HSTRS can be enhanced under the MRS scheme with a certain level of hardware impairments at the HSTRS.

The remainder of this paper is organized as follows. In Section II, the system model of a multiple relays assisted satellite communications systems is presented along with the single relay selection (SRS) and MRS schemes. Section III derives the closed-form outage probability expressions of the SRS and MRS schemes when the hardware is impaired in HSTRS. Next, expressions for the asymptotic outage probability associated with the DF protocol in the SRS and MRS schemes are obtained in section IV. Then, numerical results of outage probability for the SRS and MRS schemes are present in Section V. Finally, Section VI concludes this paper.

II. SYSTEM MODEL AND RELAY SELECTION SCHEMES

A. SYSTEM MODEL

Consider a HSTRS wherein a GEO satellite source S communicates with a terrestrial destination D via N terrestrial relays denoted by $R_1, R_2, \ldots, R_N$, which is presented in Fig. 1. Here, all terminals are assumed to be equipped with a single antenna and the relays employ the DF protocol.

TABLE 1. List of abbreviations.

Original words	Abbreviations
hybrid satellite-terrestrial relay systems	HSTRS
geosynchronous earth orbit	GEO
decode-and-forward	DF
multi-relay selection	MRS
single relay selection	SRS
amplify-and-forward	AF
line of sight	LoS
symbol error rate	SER
land mobile satellite	LMS
multiple-input multiple-output	MIMO
two-way satellite relaying	TWSR
channel state information	CSI
cognitive hybrid satellite-terrestrial network	CSTRN
mean squared error	MSE
additive white Gaussian noise	AWGN
signal-to-noise-ratio	SNR
signal-to-noise-and-distortion-ratio	SNDR
probability distribution function	PDF
cumulative distribution function	CDF

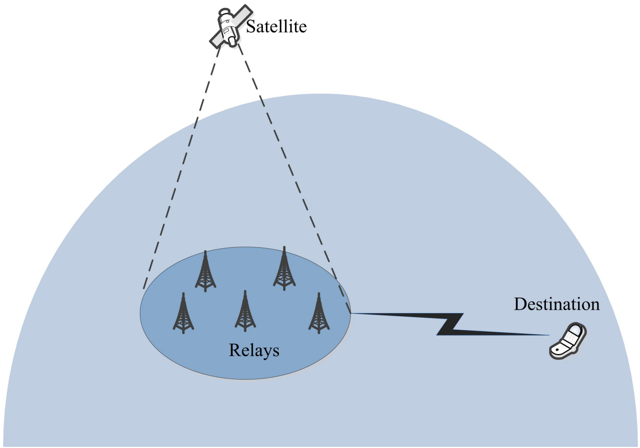


FIGURE 1. HSTRS composed of a source (S) and a destination (D) and N relays.

Due to large separation and heavy shadowing, the direct channel between satellite and the destination is assumed to be blocked. Additionally, we also assume the global CSI of all links are available. Typically, accurate CSI may be obtained through pilot-aided channel estimation methods [38]. Moreover, the estimated CSI accuracy can be further improved by increasing the pilot signal overhead.

Generally, the Shadowed-Rician fading model is suitable for satellite links, which is a popular land mobile satellite fading channel model derived in [39]. Following the existing satellite literature [15], [31], [32], we assume that the channels from the satellite to different terrestrial relays are independent and identically distributed (i.i.d) flat fading channels. Thus, under the fading model of Shadowed-Rician, the probability distribution function (PDF) of the power channel gain $|h_{si}|^2$ (from satellite to i-th relay, $i = 1, 2, \cdots, N$) is given by

$$f_{|h_{si}|^2}(x) = \alpha_i e^{-\beta_i x} {}_1F_1(m_i; 1; \delta_i x), x \geq 0, \tag{1}$$

where $\alpha_i = \frac{1}{2b_i}\left(\frac{2b_i m_i}{2b_i m_i+\Omega_i}\right)^{m_i}$, $\beta_i = \frac{1}{2b_i}$, $\delta_i = \frac{\Omega_i}{2b_i(2b_i m_i+\Omega_i)}$, the parameter Ω_i represents the average power of the LoS component, $2b_i$ is the average power of the multipath component and m_i is the Nakagami parameter ranging from 0 to ∞. When $m_i = 0$ the envelope of h_{si} becomes a Rayleigh PDF and it becomes a Rice PDF when $m_i = \infty$.

Given $\bar{\gamma}$ as the average signal-to-noise ratio (SNR) and $\gamma_{si} = |h_{si}|^2\bar{\gamma}$, the PDF of γ_{si} can be obtained as

$$\begin{aligned} f_{\gamma_{si}}(x) &= \frac{1}{\bar{\gamma}} \times f_{|h_{si}|^2}(\frac{x}{\bar{\gamma}}) \\ &= \frac{\alpha_i}{\bar{\gamma}} e^{-\frac{\beta_i}{\bar{\gamma}}x} {}_1F_1(m_i; 1; \delta_i x), x \geq 0. \end{aligned} \tag{2}$$

The cumulative distribution function (CDF) of γ_{si} can be derived by employing the Maclaurin series expansion for the exponential function e^{-x}, yielding

$$\begin{aligned} F_{\gamma_{si}}(x) &= \frac{\alpha_i}{\bar{\gamma}} x {}_1F_1(m_i; 2; \frac{\delta_i x}{\bar{\gamma}}) \\ &+ \sum_{j=1}^{\infty} (-1)^j \frac{\alpha_i \beta_i{}^j x^{(j+1)}}{(j+1)!\bar{\gamma}^{(j+1)}} {}_2F_2(j+1, m_i; j+2, 1; \frac{\delta_i x}{\bar{\gamma}}). \end{aligned} \tag{3}$$

where ${}_pF_q(a; b; z)$ is the confluent hypergometric function defined in [40, Definition (9.100)].

The terrestrial link of the relay to destination is modeled as a Rayleigh fading channel. Therefore, $|h_{id}|^2$ follows an exponential distribution with PDF given by

$$f_{|h_{id}|^2}(x) = \frac{1}{\delta_{id}^2} \exp(-\frac{x}{\delta_{id}^2}), \quad x \geq 0, \tag{4}$$

where δ_{id}^2 is the average power of the multipath component of the i-th channel from the relay to destination.

B. SINGLE-RELAY SELECTION

In this subsection, we consider the HSTRS, where terrestrial destination is not within the coverage area of the satellite and N terrestrial relays are utilized for transmitting the satellite signal. The DF relaying protocol is employed for the relays in transmitting the satellite signal to the terrestrial destination. More specifically, the satellite firstly broadcasts x to the terrestrial N relays and the relays will try to decode x. Here, let D denotes the decoding set in which relays could decode satellite signal successfully. Note that there are 2^N possible decoding subsets for N relays, correspondingly, the sample space of D can be formulated as

$$\Omega = \{\phi, D_1, D_2, \ldots, D_n, \ldots, D_{2^N-1}\}, \tag{5}$$

where ϕ is the empty set with no possible relays and D_n represents the n-th non-null subset of N terrestrial relays. While decoding set D is empty, which means that no relay could decode x successfully, that is to say, none of relays retransmit the satellite signal. If the set D is not empty, the relay associated with the highest capacity to the destination would be selected from the set for transmitting x. Without loss of generality, we consider that the satellite S transmits

x to the relays, thus the signal received at the i-th terrestrial relay can be expressed as

$$y_i = h_{si}(x + \eta_s) + \eta_i + v_i, \tag{6}$$

where h_{si} represents the fading coefficient between the satellite and the i-th relay, the transmit power of x is P, η_s and η_i are the distortion noises with zero mean and variance ${k_s}^2P$ and $k_i^2|h_{si}|^2P$ respectively. In addition, k_s and k_i are used to characterize the level of hardware impairments of S and the i-th R respectively. The variable v_i is the additive white Gaussian noise (AWGN) with the power N_0 at the i-th relay. From (6), the signal-to-noise-and-distortion-ratio (SNDR) of first slot can be derived as

$$\gamma_i = \frac{P|h_{si}|^2}{P|h_{si}|^2({k_s}^2 + {k_i}^2) + N_0} = \frac{\bar{\gamma}|h_{si}|^2}{\bar{\gamma}|h_{si}|^2({k_s}^2 + {k_i}^2) + 1}. \tag{7}$$

From (7), we can get the capacity between the satellite and the i-th relay as

$$C_{si} = \frac{1}{2}\log_2\left(1 + \frac{\bar{\gamma}|h_{si}|^2}{\bar{\gamma}|h_{si}|^2({k_s}^2 + {k_i}^2) + 1}\right), \tag{8}$$

where $\frac{1}{2}$ results from the matter that two time phases are required to finish the transmission of the satellite to the destination via relays. According to the Shannon coding theorem, if the channel capacity is lower than the data rate, the receiver is not able to recover the satellite signal. Thus, by using (8), the event $D = \phi$ is described as

$$C_{si} < R_s, i = 1, 2, \ldots, N, \tag{9}$$

where R_s is the transmission data rate. The $D = D_n$ can be described as

$$\begin{aligned} C_{si} &> R_s, i \in D_n \\ C_{sj} &< R_s, j \in \overline{D}_n, \end{aligned} \tag{10}$$

where $\overline{D}_n$ is the set of relays failing decoding the signal x. Then, the i-th relay is viewed as the "best" relay, which forwards the decoded source signal x to D. Hence, the received signal from i-th relay at D is

$$y_d = h_{id}(x + \eta_i) + \eta_d + v_d \tag{11}$$

where h_{id} is the fading coefficient of the i-th R to D channel. η_i and η_d are the distortion noises with zero mean and variance k_i^2P and $k_d^2|h_{id}|^2P$ respectively. In addition, k_i and k_d are used to characterize the level of hardware impairments of the i-th R and D respectively. The quantity v_d is the AWGN with the power N_0 at the destination node. From (11), the SNDR of the second slot can be derived as

$$\gamma_d = \frac{P|h_{id}|^2}{P|h_{id}|^2({k_i}^2 + {k_d}^2) + N_0} = \frac{\bar{\gamma}|h_{id}|^2}{\bar{\gamma}|h_{id}|^2({k_i}^2 + {k_d}^2) + 1}. \tag{12}$$

From (12), the channel capacity from the i-th relay to the destination is given by

$$C_{id} = \frac{1}{2}\log_2\left(1 + \frac{\bar{\gamma}|h_{id}|^2}{\bar{\gamma}|h_{id}|^2({k_i}^2 + {k_d}^2) + 1}\right), \tag{13}$$

where $i \in D_n$. Generally, the relay which has the highest capacity between the i-th relay and D is considered as the only "best" one relay. Hence, from (13), we get the selection standard of finding the only "best" relay as

$$\begin{aligned} BR &= \arg \mathop{max}_{i \in D_n} C_{id} \\ &= \arg \mathop{max}_{i \in D_n} \frac{\bar{\gamma}|h_{id}|^2}{\bar{\gamma}|h_{id}|^2({k_i}^2 + {k_d}^2) + 1} \end{aligned} \tag{14}$$

Combining (13) and (14), the channel capacity of between "best" relay and D can be obtained as

$$C_{bd} = \frac{1}{2}\log_2\left(1 + \max_{i \in D_n} \frac{\bar{\gamma}|h_{id}|^2}{\bar{\gamma}|h_{id}|^2({k_i}^2 + {k_d}^2) + 1}\right). \tag{15}$$

Here, subscript 'b' denotes the "best" relay.

C. MULTI-RELAY SELECTION

In this section, we propose a MRS scheme to mitigate an adverse effect of hardware impairments on the outage performance of HSTRS. In this selection scheme, all relays within D_n are employed for forwarding x to D simultaneously. The most apparent difference between the SRS scheme is that there is only one single "best" relay selected from D_n to forward signal in the SRS scheme. A weight vector denoted by $\mathbf{w} = [w_1, w_2, \ldots w_{|D_n|}]^T$ is used by all relays from the set D_n in forwarding x, where $|D_n|$ is the cardinality of D_n. To compare with the SRS scheme fairly, the whole transmit power of all relays of set D_n is considered to P. The level of hardware impairments within D_n are assumed to be equal. Then the signal received from relays at D is

$$y_d^{multi} = \mathbf{w}^T\mathbf{h_d}(x + \eta_i) + \eta_d + v_d, \tag{16}$$

where $\mathbf{h_d} = [h_{1d}, h_{2d}, \ldots, h_{|D_n|d}]^T$. From (16), the SNDR at D is given by

$$SNDR_d^{multi} = \frac{\bar{\gamma}\left|w^T h_d\right|^2}{\bar{\gamma}\left|w^T h_d\right|^2({k_i}^2 + {k_d}^2) + 1}. \tag{17}$$

Here, we are ought to maximize the $SNDR_d^{multi}$ to optimize the vector $\mathbf{w}$, yielding

$$\max_{\mathbf{w}} \; SNDR_d^{multi}, \; s.t. \; \|\mathbf{w}\| = 1, \tag{18}$$

we can get the optimal constraint $\mathbf{w_{opt}}$ from (18) by using the Cauchy-Schwarz inequality,

$$\mathbf{w_{opt}} = \frac{\mathbf{h_d}^*}{|\mathbf{h_d}|}, \tag{19}$$

where the constraint $\mathbf{w_{opt}}$ is used for normalization. Substituting $\mathbf{w_{opt}}$ from (19) into (17), we get the channel capacity achieved at D as

$$C_d^{multi} = \frac{1}{2}\log_2\left(1 + \frac{\bar{\gamma}\sum\limits_{i\in D_n}|h_{id}|^2}{\bar{\gamma}(k_i^2+k_d^2)\sum\limits_{i\in D_n}|h_{id}|^2+1}\right). \tag{20}$$

III. OUTAGE ANALYSIS OF THE HSTRS WITH HARDWARE IMPAIRMENTS

In this section, we propose a MRS scheme to decrease the outage probability when hardware impairments exist. For comparison purpose, we take the SRS scheme as the baseline. Their closed-form expressions will be derived and analyzed respectively.

A. SINGLE-RELAY SELECTION

Here, we present the SRS scheme as benchmark. Using the law of total probability, the outage probability of the SRS scheme is given by

$$\begin{aligned} P_{out}^{single} &= \Pr(C_{bd} < R_s, D = \phi) \\ &\quad + \sum_{n=1}^{2^N-1}\Pr(C_{bd} < R_s, D = D_n), \end{aligned} \tag{21}$$

where C_{bd} represents the capacity of the channel spanning from the best relay to D. In the case of $D = \phi$, no relay is chosen to forward the satellite signal, leading to $C_{bd} = 0$. Thus, the (21) can be expressed as

$$\begin{aligned} P_{out}^{single} &= \Pr(D = \phi) \\ &\quad + \sum_{n=1}^{2^N-1}\Pr(D = D_n)\Pr(C_{bd} < R_s), \end{aligned} \tag{22}$$

Using (3) and (9), we can obtain

$$\begin{aligned} \Pr(D = \phi) &= \prod_{i=1}^{N}\Pr(C_{si} < R_s) \\ &= \prod_{i=1}^{N}\Pr\left(\bar{\gamma}|h_{si}|^2 < \frac{2^{2R_s-1}}{1-(2^{2R_s-1})(k_s^2+k_i^2)}\right) \\ &= \prod_{i=1}^{N}\Pr(\bar{\gamma}|h_{si}|^2 < \gamma_{th}) \\ &= \prod_{i=1}^{N}F_{\gamma_{si}}(\gamma_{th}) \end{aligned} \tag{23}$$

and

$$\begin{aligned} \Pr(D = D_n) &= \prod_{i\in D_n}\Pr(\gamma_{si} > \gamma_{th})\prod_{j\in \bar{D}_n}\Pr(\gamma_{sj} < \gamma_{th}) \\ &= \prod_{i\in D_n}(1 - F_{\gamma_{si}}(\gamma_{th}))\prod_{j\in \bar{D}_n}F_{\gamma_{sj}}(\gamma_{th}), \end{aligned} \tag{24}$$

where $\gamma_{th} = \frac{2^{2R_s}-1}{1-(2^{2R_s}-1)({k_s}^2+{k_i}^2)}$. The link between the satellite and the relay is assumed as Shadowed-Rician distribution, according to (3), the $F_{\gamma_{si}}(\gamma_{th})$ can be easily written as

$$\begin{aligned} F_{\gamma_{si}}(\gamma_{th}) &= \frac{\alpha_0\gamma_{th}}{\bar{\gamma}}{}_1F_1(m_0; 2; \frac{\delta_0\gamma_{th}}{\bar{\gamma}}) \\ &\quad + \sum_{j=1}^{\infty}(-1)^j\frac{\alpha_0{\beta_0}^j{\gamma_{th}}^{(j+1)}}{(j+1)!\bar{\gamma}^{(j+1)}}{}_2F_2(j+1, m_0; j+2, 1; \frac{\delta_0\gamma_{th}}{\bar{\gamma}}), \end{aligned} \tag{25}$$

where $\alpha_0 = \frac{1}{2b_0}\left(\frac{2b_0m_0}{2b_0m_0+\Omega_0}\right)^{m_0}$, $\beta_0 = \frac{1}{2b_0}$, $\delta_0 = \frac{\Omega_0}{2b_0(2b_0m_0+\Omega_0)}$.

Then, (22) can be further expressed as

$$\begin{aligned} P_{out}^{single} &= \prod_{i=1}^{N}F_{\gamma_{si}}(\gamma_{th}) + \sum_{n=1}^{2^N-1}\prod_{i\in D_n}(1 - F_{\gamma_{si}}(\gamma_{th})) \\ &\quad \prod_{j\in \bar{D}_n}F_{\gamma_{sj}}(\gamma_{th}) \times \Pr\left(\max_{i\in D_n}|h_{id}|^2 < \frac{\gamma_{th}}{\bar{\gamma}}\right), \end{aligned} \tag{26}$$

Noting that $|h_{id}|^2$ follows an exponentially distributed random variables with means of δ_{id}^2, we obtain

$$\Pr\left(\max_{i\in D_n}|h_{id}|^2 < \frac{\gamma_{th}}{\bar{\gamma}}\right) = \prod_{i\in D_n}\left(1 - \exp\left(-\frac{\gamma_{th}}{\bar{\gamma}\delta_{id}^2}\right)\right) \tag{27}$$

Combining (3), (26) and (27), we can derive the closed-form expressions of the SRS scheme with hardware impairments.

B. MULTI-RELAY SELECTION

The outage probability of the MRS scheme is given by

$$\begin{aligned} P_{out}^{multi} &= \Pr(D = \phi) \\ &\quad + \sum_{n=1}^{2^N-1}\Pr(D = D_n)\Pr(C_d^{multi} < R_s). \end{aligned} \tag{28}$$

Using (9), (10) and (20), we can rewrite (28) as

$$\begin{aligned} P_{out}^{multi} &= \prod_{i=1}^{N}F_{\gamma_{si}}(\gamma_{th}) + \sum_{n=1}^{2^N-1}\prod_{i\in D_n}(1 - F_{\gamma_{si}}(\gamma_{th})) \\ &\quad \prod_{j\in \bar{D}_n}F_{\gamma_{sj}}(\gamma_{th}) \times \Pr(C_d^{multi} < R_s). \end{aligned} \tag{29}$$

In (29), $P(C_d^{multi} < R_s)$ can be further expressed as

$$\begin{aligned} &\Pr\left(\frac{1}{2}\log_2(1 + \frac{\bar{\gamma}\sum\limits_{i\in D_n}|h_{id}|^2}{\bar{\gamma}(k_i^2+k_d^2)\sum\limits_{i\in D_n}|h_{id}|^2+1}) < R_s\right) \\ &\qquad = \Pr\left(\sum_{i\in D_n}|h_{id}|^2 < \frac{\gamma_{th}}{\bar{\gamma}}\right). \end{aligned} \tag{30}$$

Comparing the expression of $\Pr\left(\sum\limits_{i\in D_n}|h_{id}|^2 < \frac{\gamma_{th}}{\bar{\gamma}}\right)$ with $\Pr\left(\max\limits_{i\in D_n}|h_{id}|^2 < \frac{\gamma_{th}}{\bar{\gamma}}\right)$, we can conclude that the outage performance of the MRS scheme performs better than the SRS scheme when hardware impairments exist. It should be remarked that the MRS scheme requires a highly complicated symbol-level synchronization when the signal copies are forwarded to the destination at the same time, while the SRS scheme does not require such complex procedure. In addition, the incomplete synchronization of the MRS scheme may lead to the degradation of reliability performance, which might even result in a reliability performance of the SRS scheme becoming better than the MRS scheme.

Unfortunately, it is difficult to obtain a general closed-form expression of $\Pr\left(\sum_{i\in D_n}|h_{id}|^2 < \frac{\gamma_{th}}{\overline{\gamma}}\right)$. For simplicity, all the fading coefficients of relay-destination channels $|h_{id}|^2$ are assumed as i.i.d random variables with an equal average channel gain represented by $\delta_d^2 = E(|h_{id}|^2)$. Thus, we can simplify $\Pr\left(\sum_{i\in D_n}|h_{id}|^2 < \frac{\gamma_{th}}{\overline{\gamma}}\right)$ by assuming that $|h_{id}|^2$ for $i \in D_n$ are i.i.d, the PDF of $X = \sum_{i\in D_n}|h_{id}|^2$ can be written as

$$f_X(x) = \frac{1}{\Gamma(|D_n|)\delta_d^{2|D_n|}} x^{|D_n|-1} e^{-\frac{x}{\delta_d^2}}, \tag{31}$$

where $\delta_d^2 = E\left(|h_{id}|^2\right)$. Using (31), we arrive at

$$\begin{aligned}
\Pr(X < \frac{\gamma_{th}}{\overline{\gamma}}) &= \int_0^{\frac{\gamma_{th}}{\overline{\gamma}}} \frac{1}{\Gamma(|D_n|)\delta_d^{2|D_n|}} x^{|D_n|-1} e^{-\frac{x}{\delta_d^2}} dx \\
&= \int_0^{\frac{\gamma_{th}}{\overline{\gamma}\delta_d^2}} \frac{z^{|D_n|-1}}{\Gamma(|D_n|)} e^{-z} dz \\
&= \Gamma(\frac{\gamma_{th}}{\overline{\gamma}\delta_d^2}, |D_n|)
\end{aligned} \tag{32}$$

where $z = \frac{x}{\delta_d^2}$ and $\int_0^a \frac{z^{k-1}}{\Gamma(k)} e^{-z} dz$ is the incomplete Gamma function in [41].

Substituting (3) and (32) into (29), we can finally obtain a closed-form expression of the outage probability of the MRS scheme in the presence of hardware impairments.

IV. ASYMPTOTIC OUTAGE PROBABILITY ANALYSIS

In the following, we conduct an asymptotic outage probability analysis in the high SNR region for the SRS and MRS schemes to provide insight into the effect of hardware impairments on the HSTRS.

A. SINGLE-RELAY SELECTION

First, for $\overline{\gamma} \to \infty$, we can expand the function in (2) with Maclaurin series. Consequently, the PDF $f_{\gamma_{si}}(x)$ becomes

$$f_{\gamma_{si}} \approx \frac{\alpha_i}{\overline{\gamma}} + o(x), \tag{33}$$

where $o(x)$ is the infinitesimal of higher order for x. Then, we can obtain an asymptotic expression for $F_{\gamma_{si}}(\gamma_{th})$

$$F_{\gamma_{si}}(\gamma_{th}) = \frac{\alpha_0}{\overline{\gamma}}\gamma_{th}. \tag{34}$$

Similarly, the PDF $f_{\gamma_{id}}(x)$ can be expressed as

$$f_{\gamma_{id}} \approx \frac{1}{\overline{\gamma}}\frac{1}{\delta_d^2} + o(x). \tag{35}$$

Next, the asymptotic expression of $F_{\gamma_{id}}(\gamma_{th})$ is given by

$$F_{\gamma_{id}}(\gamma_{th}) = \frac{1}{\delta_d^2}\frac{\gamma_{th}}{\overline{\gamma}}. \tag{36}$$

According to (36), we can obtain

$$\Pr\left(\max_{i\in D_n}|h_{id}|^2 < \frac{\gamma_{th}}{\overline{\gamma}}\right) = \prod_{i\in D_n}\left(\frac{1}{\delta_d^2}\frac{\gamma_{th}}{\overline{\gamma}}\right). \tag{37}$$

Substituting (34) and (37) into (22), we can obtain an asymptotic outage probability expression for the SRS scheme.

B. MULTI-RELAY SELECTION

According to (32), we can write $f_{\overline{\gamma}_X}(x)$ as

$$f_{\overline{\gamma}_X}(x) = \frac{1}{\overline{\gamma}}\frac{1}{\Gamma(|D_n|)\delta_d^{2|D_n|}}\left(\frac{x}{\overline{\gamma}}\right)^{|D_n|-1} e^{-\frac{x}{\overline{\gamma}\delta_d^2}}. \tag{38}$$

The PDF $f_{\overline{\gamma}_X}(x)$ can be expanded as (39), shown at the bottom of this page, with Maclaurin series. Here, the first order of $x-1$ is considered.

Then, we can get the asymptotic expression of $\Pr\left(\sum_{i\in D_n}|h_{id}|^2 < \frac{\gamma_{th}}{\overline{\gamma}}\right)$ in (40), as shown at the bottom of this page.

Finally, substituting (34) and (40) into (29), we can obtain an asymptotic outage probability expression for the MRS scheme.

$$\begin{aligned}
f_{\overline{\gamma}_X}(x) &\approx f_{\overline{\gamma}_X}(1) + f_{\overline{\gamma}_X}{}'(1)(x-1) + o(x-1)^2 \\
&= \left(\frac{1}{\overline{\gamma}}\right)^{|D_n|}\frac{1}{\Gamma(|D_n|)\delta_d^{2|D_n|}} e^{-\frac{1}{\overline{\gamma}\delta_d^2}} + \left(\frac{1}{\Gamma(|D_n|)\delta_d^{2|D_n|}}\right)\left(\left(\frac{1}{\overline{\gamma}}\right)^{|D_n|} e^{-\frac{1}{\overline{\gamma}\delta_d^2}}\right)\left(|D_n| - 1 - \frac{1}{\overline{\gamma}\delta_d^2}\right)(x-1) + o(x-1)^2
\end{aligned} \tag{39}$$

$$\begin{aligned}
F_{\overline{\gamma}_X}(\gamma_{th}) = {} & \frac{1}{\Gamma(|D_n|)\delta_d^{2|D_n|}} e^{-\frac{1}{\overline{\gamma}\delta_d^2}}\left(\frac{1}{\overline{\gamma}}\right)^{|D_n|}\left(2 + \frac{1}{\overline{\gamma}\delta_d^2} - |D_n|\right)\gamma_{th} \\
& + \frac{1}{2}\left(\frac{1}{\Gamma(|D_n|)\delta_d^{2|D_n|}}\right)\left(\left(\frac{1}{\overline{\gamma}}\right)^{|D_n|} e^{-\frac{1}{\overline{\gamma}\delta_d^2}}\right)\left(|D_n| - 1 - \frac{1}{\overline{\gamma}\delta_d^2}\right)\gamma_{th}^2
\end{aligned} \tag{40}$$

V. NUMERICAL RESULTS AND DISCUSSIONS

In this section, we provide simulation results to verify the outage performance in the HSTRS relaying on the SRS and MRS schemes respectively when hardware impairments exist. In our numerical results, the Shadowed-Rician fading parameters are considered as $(b, m, \Omega) = (0.126, 10.1, 0.835)$ [39]. The average channel gains of the Rayleigh fading are specified as $\delta_{id}^2 = 1$.

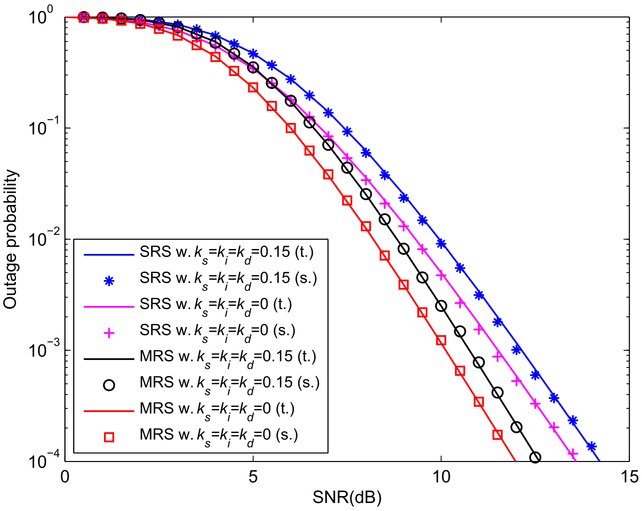


FIGURE 2. Outage probability versus the transmit power SNR of the SRS and MRS schemes for both ideal hardware and impaired hardware scenarios with data rate R_S=1 bit/s/Hz.

Fig. 2 shows the outage probability versus SNR for both ideal and impaired hardware scenarios, where discrete markers and solid lines represent the simulated (s.) and theoretical (t.) outage probability results, respectively. We assume that all nodes are with the same level of hardware impairments, which means $k_s = k_i = k_d$. In Fig. 2, $k_s = k_i = k_d = 0$ means that all nodes are ideal hardware. As the hardware impairments level increases from $k_s = k_i = k_d = 0$ to 0.15, the outage performance of HSTRS would degrade for both the SRS and MRS schemes. Additionally, the outage performance of the MRS scheme is much better than that of the SRS scheme given an equal level of the hardware impairments.

Fig. 3 demonstrates the outage probability versus SNR of the SRS and MRS schemes for different data rates of $R_s = 0.8$bit/s/Hz and $R_s = 1$bit/s/Hz with a given hardware impairments level of $k_s = k_i = k_d = 0.15$. As shown in Fig. 3, given a hardware impairments level, the MRS scheme significantly outperforms the SRS scheme for both the cases of $R_s = 0.8$bit/s/Hz and 1bit/s/Hz. Moreover, as the data rate increases from $R_s = 0.8$bit/s/Hz to 1bit/s/Hz, the outage performance of the SRS and MRS schemes degrades accordingly.

In Fig. 4, we show the outage probability versus SNR of the SRS and MRS schemes for $N = 2$ and 6 with a given hardware impairments level of $k_s = k_i = k_d = 0.15$. Fig. 4 shows that for both the cases of $N = 2$ and 6, the SRS scheme performs worse than the MRS scheme in terms of the outage probability. In addition, as the number of relays increases from $N = 2$ to 6, the outage performance of both the SRS and MRS schemes enhances, implying that the outage probability can be reduced by increasing the number of relays.

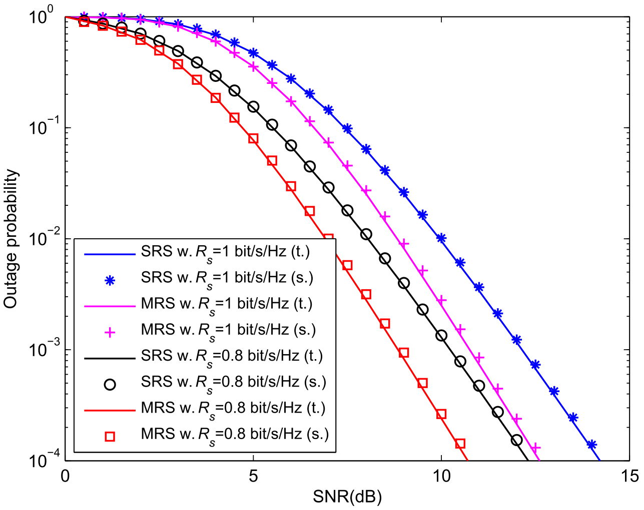


FIGURE 3. Outage probability versus the transmit power SNR of the SRS and MRS schemes for different data rates R_S when the hardware impairments level is 0.15.

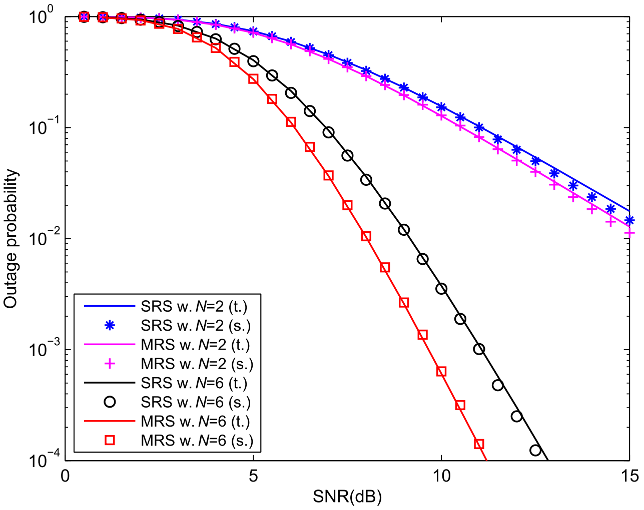


FIGURE 4. Outage probability versus the transmit power SNR of the SRS and MRS schemes in different number of relays when the hardware impairments level is 0.15.

Fig. 5 depicts the outage probability versus the hardware impairments level for the different number of relays of $N = 4$ and $N = 6$ with a data rate of $R_s = 1$bit/s/Hz and an SNR of 10 dB. As observed from Fig. 5, the outage probabilities of the SRS and MRS schemes increase with an increasing hardware impairments level. When the hardware impairments level increases beyond a threshold, the outage probabilities of both the SRS and MRS schemes increase to one and then keeps unchanged, indicating that the outage probability is significantly influenced by the impaired hardware.

In Fig. 6, we show the outage probability versus the number of relays for different hardware impairments levels of $k_s = k_i = k_d = 0$ and 0.15 with a data rate $R_s = 1$bit/s/Hz and an SNR of 10dB. As shown in Fig. 6, the outage probabilities of

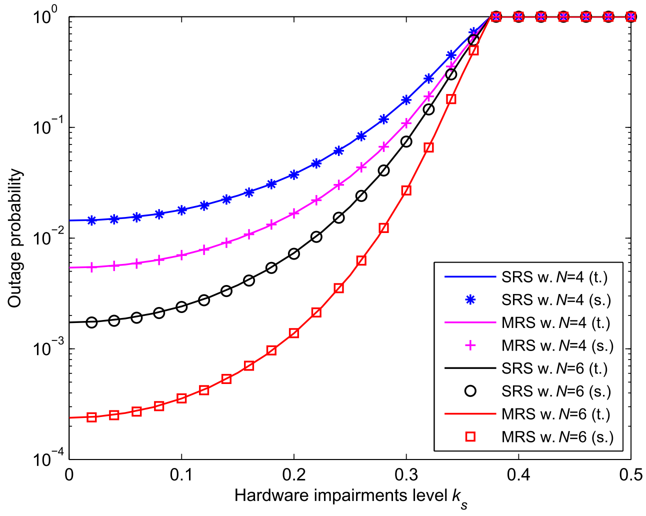


FIGURE 5. Outage probability versus the hardware impairments k_s of the SRS and MRS schemes in different number of relays when the SNR is 10 dB.

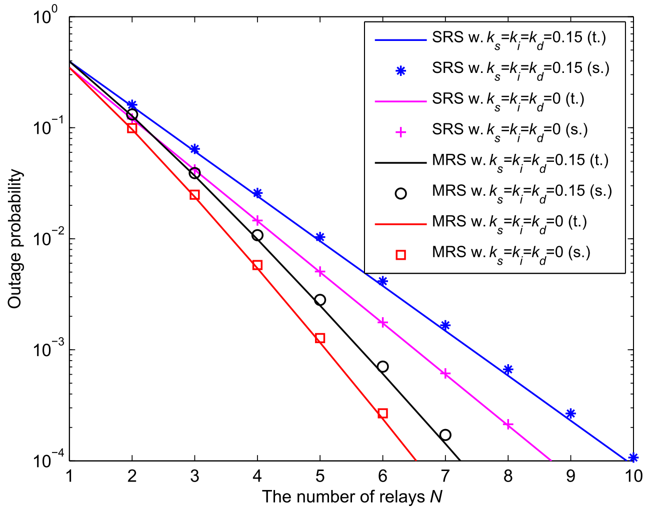


FIGURE 6. Outage probability versus the number of relays of the SRS and MRS schemes for both ideal and impaired hardware when the SNR is 10 dB.

both the SRS and MRS schemes significantly decrease with the increase of the number of relays. Moreover, as the level of hardware impairments increases from 0 to 0.15, the outage performance of both the SRS and MRS schemes degrades accordingly.

Fig. 7 plots the asymptotic and exact outage probabilities versus SNR for both the SRS and MRS schemes. As shown from Fig. 7, the asymptotic and exact outage probabilities match well with each other in the high SNR region, which validates the correctness of our asymptotic outage probability analysis.

Fig. 8 shows the outage probability versus the SNR of the SRS and MRS schemes relying on DF and AF protocols with a hardware impairment level of $k_s = 0.15$ and a data rate of $R_s = 1$bit/s/Hz. As shown in Fig. 7, when the AF protocol is employed at relays, the outage performance would degrade significantly compared with DF protocol for both the SRS and MRS schemes, which shows the advantage of the DF protocol over the AF protocol.

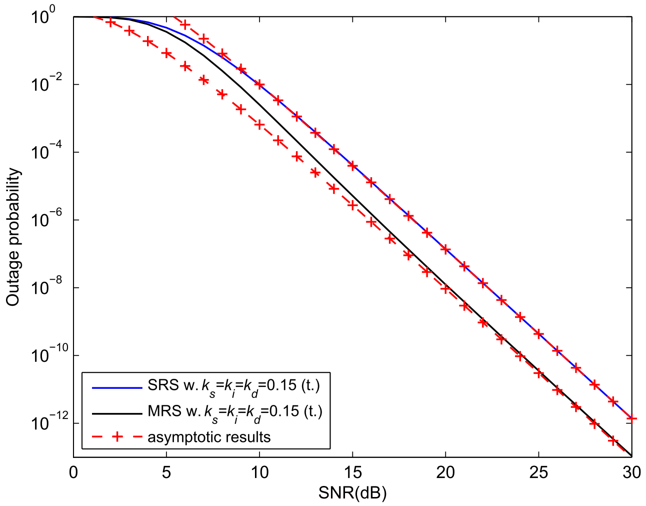


FIGURE 7. The asymptotic analysis in high SNR region for the outage probability for both the SRS and MRS schemes when employing DF protocol.

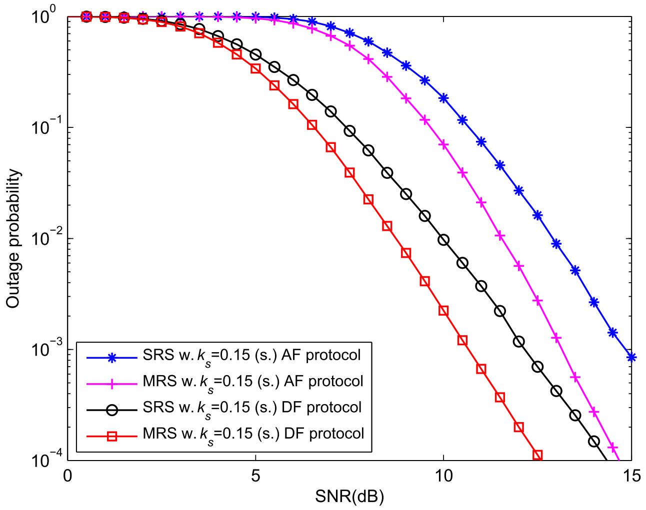


FIGURE 8. Outage probability versus the SNR of the SRS and MRS schemes of the DF protocol and AF protocol when the hardware impairment level is 0.15.

VI. CONCLUSION

In this paper, we have investigated the effect of hardware impairments on the reliability performance of HSTRS composed of a geostationary satellite, a terrestrial destination and multiple terrestrial relays. We proposed the MRS scheme to mitigate the adverse effect of hardware impairments on the outage performance of HSTRS. Also, we considered the SRS scheme as a baseline. Closed-form and asymptotic expressions of outage probability for both the SRS and MRS schemes were derived. It was shown that the outage probability of HSTRS was degraded by the hardware impairments. Moreover, the outage performance of HSTRS can be enhanced by employing the MRS scheme compared to the SRS scheme. In addition, upon increasing the number of relays, the outage probabilities of both the SRS and MRS schemes are substantially reduced in the face of a certain level of hardware impairments. Additionally, when relays employ the AF protocol, the outage performance for both the SRS and MRS schemes would degrade accordingly compared with the DF protocol.

REFERENCES

[1] B. Evans *et al.*, "Integration of satellite and terrestrial systems in future multimedia communications," *IEEE Wireless Commun.*, vol. 12, no. 5, pp. 72–80, Oct. 2005.

[2] G. Zheng, S. Chatzinotas, and B. Ottersten, "Generic optimization of linear precoding in multibeam satellite systems," *IEEE Trans. Wireless Commun.*, vol. 11, no. 6, pp. 2308–2320, Jun. 2012.

[3] A. Vaneli-Corali *et al.*, "Satellite communications: Research trends and open issues." in *Proc. Int. Workshop Satell. Space Commun.*, Salzburg, Austria, Sep. 2007, pp. 71–75.

[4] M. R. Bhatnagar, and M. K. Arti, "Performance analysis of AF based hybrid satellite-terrestrial cooperative network over generalized fading channels," *IEEE Commun. Lett.*, vol. 17, no. 10, pp. 1912–1915, Oct. 2013.

[5] V. K. Sakarellos, C. Kourogiorgas, and A. D. Panagopoulos, "Cooperative hybrid land mobile satellite-terrestrial broadcasting systems: Outage probability evaluation and accurate simulation," *Wireless Pers. Commun.*, vol. 79, no. 2, pp. 1471–1481, Nov. 2014.

[6] M. K. Arti and V. Jain, "Relay selection-based hybrid satellite-terrestrial communication systems," *IET Commun.*, vol. 11, no. 17, pp. 2566–2574, Nov. 2017.

[7] S. Sreng, B. Escrig, and M.-L. Boucheret, "Exact outage probability of a hybrid satellite terrestrial cooperative system with best relay selection," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Budapest, Hungary, Jun. 2013, pp. 4520–4524.

[8] K. An, M. Lin, J. Ouyang, Y. Huang, and G. Zheng, "Symbol error analysis of hybrid satellite-terrestrial cooperative networks with cochannel interference," *IEEE Commun. Lett.*, vol. 18, no. 11, pp. 1947–1950, Nov. 2014.

[9] M. K. Arti and M. R. Bhatnagar, "Beamforming and combining in hybrid satellite-terrestrial cooperative systems," *IEEE Commun. Lett.*, vol. 18, no. 3, pp. 483–486, Mar. 2014.

[10] M. R. Bhatnagar and M. K. Arti, "Performance analysis of hybrid satellite-terrestrial FSO cooperative system," *IEEE Photon. Technol. Lett.*, vol. 25, no. 22, pp. 2197–2200, Nov. 2013.

[11] K. An, M. Lin, T. Liang, J. Ouyang, C. Yuan, and Y. Li, "Secure transmission in multi-antenna hybrid satellite-terrestrial relay networks in the presence of eavesdropper," in *Proc. Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Nanjing, China, Oct. 2015, pp. 1–5.

[12] Y. Zou, J. Zhu, X. Wang, and L. Hanzo, "A survey on wireless security: Technical challenges, recent advances, and future trends," *Proc. IEEE*, vol. 104, no. 9, pp. 1727–1765, Sep. 2016.

[13] M. K. Arti, "Imperfect CSI based AF relaying in hybrid satellite-terrestrial cooperative communication systems," in *Proc. IEEE Int. Conf. Commun. Workshop (ICCW)*, London, U.K., Jun. 2015, pp. 1681–1686.

[14] P. K. Upadhyay and P. K. Sharma, "Multiuser hybrid satellite-terrestrial relay networks with co-channel interference and feedback latency," in *Proc. Eur. Conf. Netw. Commun. (EuCNC)*, Athens, Greece, Jun. 2016, pp. 174–178.

[15] K. Guo, M. Lin, B. Zhang, W.-P. Zhu, J.-B. Wang, and T. A. Tsiftsis, "On the performance of LMS communication with hardware impairments and interference," *IEEE Trans. Commun.*, vol. 67, no. 2, pp. 1490–1505, Feb. 2019.

[16] D. S. Gurjar and P. K. Upadhyay, "Impact of channel estimation error on zero-forcing-based multiple-input-multiple-output two-way relaying," *IET Signal Process.*, vol. 10, no. 3, pp. 210–217, May 2016.

[17] S. S. Ikki, "Performance analysis of cooperative diversity networks with imperfect channel estimation over Rician fading channels," *IET Signal Process.*, vol. 6, no. 6, pp. 577–583, Aug. 2012.

[18] M. R. Bhatnagar, "Making two-way satellite relaying feasible: A differential modulation based approach," *IEEE Trans. Commun*, vol. 63, no. 8, pp. 2836–2847, Aug. 2015.

[19] M. K. Arti, "Two-way satellite relaying with estimated channel gains," *IEEE Trans. Commun.*, vol. 64, no. 7, pp. 2808–2820, Jul. 2016.

[20] K. Guo, B. Zhang, Y. Huang, and D. Guo, "Performance analysis of two-way satellite terrestrial relay networks with hardware impairments," *IEEE Wireless Commun. Lett.*, vol. 6, no. 4, pp. 430–433, Aug. 2017.

[21] M. K. Arti, "Channel estimation and detection in hybrid satellite-terrestrial communication systems," *IEEE Trans. Veh. Technol.*, vol. 65, no. 7, pp. 5764–5771, Jul. 2016.

[22] E. Costa and S. Pupolin, "M-QAM-OFDM system performance in the presence of a nonlinear amplifier and phase noise," *IEEE Trans. Commun.*, vol. 50, no. 3, pp. 462–472, Mar. 2002.

[23] T. Schenk, *RF Imperfections in High-Rate Wireless Systems: Impact and Digital Compensation*. Springer, 2008, pp. 2033–2043.

[24] C. Studer, M. Wenk, and A. Burg, "MIMO transmission with residual transmit-RF impairments," in *Proc. Int. ITG Workshop Smart Antennas (WSA)*, Bremen, Germany, Feb. 2010, pp. 189–196.

[25] E. Bjornson, M. Matthaiou, and M. Debbah, "A new look at dual-hop relaying: Performance limits with hardware impairments," *IEEE Trans. Commun.*, vol. 61, no. 11, pp. 4512–4525, Nov. 2013.

[26] X. Zhang, M. Matthaiou, M. Coldrey, and E. Björnson, "Impact of residual transmit RF impairments on training-based MIMO systems," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2014, pp. 4741–4746.

[27] J. Qi, S. Aissa, and M.-S. Alouini, "Analysis and compensation of I/Q imbalance in amplify-and-forward cooperative systems," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2012, pp. 215–220.

[28] K. Guo, J. Chen, Y. Huang, G. Li, and N. Liu, "Outage and capacity analysis between opportunistic and partial relay cooperative network with hardware impairments," in *Proc. Int. Workshop High Mobility Wireless Commun.*, Beijing, China, Nov. 2014, pp. 78–83.

[29] K. Guo, J. Chen, G. Li, and X. Wang, "Outage analysis of cooperative cellular network with hardware impairments," in *Proc. Int. Conf. Inf. Sci. Electron. Elect. Eng.*, Sapporo, Japan, Apr. 2014, pp. 1416–1420.

[30] K. Guo, B. Zhang, Y. Huang, and D. Guo, "Outage analysis of multi-relay networks with hardware impairments using SECps scheduling scheme in shadowed-Rician channel," *IEEE Access*, vol. 5, pp. 5113–5120, 2017.

[31] K. Guo, K. An, B. Zhang, Y. Huang, and G. Zheng, "Outage analysis of cognitive hybrid satellite-terrestrial networks with hardware impairments and multi-primary users," *IEEE Wireless Commun. Lett.*, vol. 7, no. 5, pp. 816–819, Oct. 2018.

[32] K. Guo, K. An, B. Zhang, Y. Huang, and D. Guo, "On the performance of cognitive satellite-terrestrial relay networks with channel estimation error and hardware impairments," *Sensors*, vol. 18, no. 10, p. 3292, 2018.

[33] K. Guo, D. Guo, and B. Zhang, "Performance analysis of two-way multi-antenna multi-relay networks with hardware impairments," *IEEE Access*, vol. 5, pp. 15971–15980, 2017.

[34] P. Clarke and R. C. de Lamare, "Transmit diversity and relay selection algorithms for multirelay cooperative MIMO systems," *IEEE Trans. Veh. Technol.*, vol. 61, no. 3, pp. 1084–1098, Mar. 2012.

[35] M. Ding, S. Liu, H. Luo, and W. Chen, "MMSE based greedy antenna selection scheme for AF MIMO relay systems," *IEEE Signal Process. Lett.*, vol. 17, no. 5, pp. 433–436, May 2010.

[36] Y. Zou, B. Champagne, W.-P. Zhu, and L. Hanzo, "Relay-selection improves the security-reliability trade-off in cognitive radio systems," *IEEE Trans. Commun.*, vol. 63, no. 1, pp. 215–228, Jan. 2015.

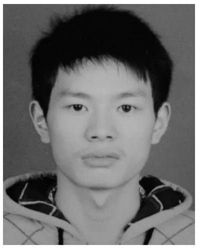
[37] J. Zhu, Y. Zou, B. Champagne, W.-P. Zhu, and L. Hanzo, "Security-reliability tradeoff analysis of multirelay-aided decode-and-forward cooperation systems," *IEEE Trans. Veh. Technol.*, vol. 65, no. 7, pp. 5825–5831, Jul. 2016.

[38] F. Benkhelifa, A. Tall, Z. Rezki, and M.-S. Alouini, "On the low SNR capacity of MIMO fading channels with imperfect channel state information," *IEEE Trans. Commun.*, vol. 62, no. 6, pp. 1921–1930, Jun. 2014.

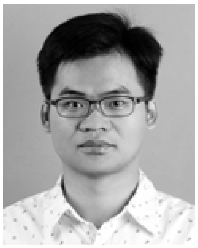
[39] A. Abdi, W. Lau, M.-S. Alouini, and M. Kaveh, "A new simple model for land mobile satellite channels: First—and second-order statistics," *IEEE Trans. Wireless Commun.*, vol. 2, no. 3, pp. 519–528, May 2003.

[40] A. P. Prudnikov, Y. A. Brychkov, and O. I. Marichev, *Integrals and Series*, vol. 3, 1st ed. New York, NY, USA: Gordon and Breach Science, 1990.

[41] L. D. Stefano and S. Mattoccia, "A sufficient condition based on the Cauchy–Schwarz inequality for efficient template matching," in *Proc. Int. Conf. Image Process.*, Catalonia, Spain, Sep. 2003, p. I-269.



HANG WU was born in Anqing, China, in 1994. He received the B.Eng. degree in communication engineering from the Anhui University of Science and Technology (AUST), Huainan, China, in 2016. He is currently pursuing the M.S. degree in signal and information processing with the Nanjing University of Posts and Telecommunications, Nanjing, China. His research interests include satellite communication and hardware impairments.



YULONG ZOU (SM'13) received the B.Eng. degree in information engineering from the Nanjing University of Posts and Telecommunications (NUPT), Nanjing, China, in 2006, the first Ph.D. degree in electrical engineering from the Stevens Institute of Technology, NJ, USA, in 2012, and the second Ph.D. degree in signal and information processing from NUPT, in 2012, where he is currently a Full Professor and Doctoral Supervisor. He was a recipient of the 9th IEEE Communications Society Asia-Pacific Best Young Researcher Award, in 2014, and a co-receipt of the Best Paper Award at the 80th IEEE Vehicular Technology Conference, in 2014. He has served as an Editor for the IEEE Communications Surveys & Tutorials, the IEEE Communications Letters, the *EURASIP Journal on Advances in Signal Processing*, the *IET Communications*, and *China Communications*. In addition, he has acted as a TPC Member for various IEEE sponsored conferences, e.g., IEEE ICC/GLOBECOM/WCNC/VTC/ICCC.

WEIFENG CAO received the B.S. degree in information engineering from Soochow University, Suzhou, China, in 2004, and the M.S. degree in pattern recognition from the Nanjing University of Posts and Telecommunications, Nanjing, China, in 2008, where she is currently pursuing the Ph.D. degree. Her research interests include satellite communications, cooperative communication, and physical layer security.

ZHONG CHEN was born in Xuzhou, Jiangsu, China. He received the B.Eng. degree in electrical and electronic engineering from University College London (UCL), in 2018. He is currently with the Nanjing University of Posts and Telecommunications (NJUPT), as an Exchanged Researcher, who is dedicated on the wireless-communications' physical layer security.

THEODOROS A. TSIFTSIS (SM'10) was born in Lamia, Greece, in 1970. He received the B.Sc. degree in physics from the Aristotle University of Thessaloniki, Greece, in 1993, the M.Sc. degree in digital systems engineering from Heriot-Watt University, Edinburgh, U.K., in 1995, the M.Sc. degree in decision sciences from the Athens University of Economics and Business, in 2000, and the Ph.D. degree in electrical engineering from the University of Patras, Greece, in 2006. He is currently a Professor with the School of Intelligence Science and Engineering, Jinan University, Zhuhai, China. He has authored or co-authored over 170 technical papers in scientific journals and international conferences. His research interests include the broad areas of cooperative communications, cognitive radio, communication theory, wireless-powered communication systems, and optical wireless communication systems.

Dr. Tsiftsis has been appointed to a two-year term as an IEEE Vehicular Technology Society Distinguished Lecturer (IEEE VTS DL), Class 2018. He acts as a Reviewer for several international journals and conferences. He has served as a Senior Editor or an Associate Editor on the Editorial Boards of IEEE Transactions on Vehicular Technology, the IEEE Communications Letters, *IET Communications*, and *IEICE Transactions on Communications*. He is currently an Area Editor of Wireless Communications II of the IEEE Transactions on Communications and an Associate Editor of the IEEE Transactions on Mobile Computing.

MANAV R. BHATNAGAR (M'04–SM'13) received the M.Tech. degree in communications engineering from IIT Delhi, New Delhi, India, in 2005, and the Ph.D. degree in wireless communications from the Department of Informatics, University of Oslo, Oslo, Norway, in 2008. From 2008 to 2009, he was a Postdoctoral Research Fellow with the University Graduate Center (UNIK), University of Oslo. He held visiting appointments with the Wireless Research Group, IIT Delhi; the Signal Processing in Networking and Communications (SPiNCOM) Group, University of Minnesota Twin Cities, Minneapolis, MN, USA; the Alcatel-Lucent Chair, Supélec, France; the Department of Electrical Computer Engineering, Indian Institute of Science, Bangaluru, India; UNIK, University of Oslo; the Department of Communications and Networking, Aalto University, Espoo, Finland; and the INRIA/IRISA Laboratory, University of Rennes, Lannion, France. He is currently a Professor with the Department of Electrical Engineering, IIT Delhi. His research interests include signal processing for multiple-input-multiple-output systems, cooperative communications, noncoherent communication systems, distributed signal processing for cooperative networks, multiuser communications, ultrawideband-based communications, free-space optical communication, cognitive radio, software-defined radio, power line communications, and satellite communications.

Dr. Bhatnagar was selected as an Exemplary Reviewer of the IEEE Communications Letters, in 2010 and 2012, and the IEEE Transactions on Communications, in 2015. He was an Editor of the IEEE Transactions on Wireless Communications, from 2011 to 2014. He has received the NASI-Scopus Young Scientist Award 2016 in engineering category and the Shri Om Prakash Bhasin Award in the field of electronics and information technology for the year 2016. He is a Fellow of the Institution of Engineering and Technology (IET), U.K., the Indian National Academy of Engineering (INAE), the Institution of Electronics and Telecommunication Engineers (IETE), India, and the Optical Society of India (OSI).

RODRIGO C. DE LAMARE (M'06–SM'10) was born in Rio de Janeiro, Brazil, in 1975. He received the Diploma degree in electronic engineering from the Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, in 1998, and the M.Sc. and Ph.D. degrees in electrical engineering from the Pontifical Catholic University of Rio de Janeiro (PUC-RIO), Rio de Janeiro, in 2001 and 2004, respectively. He was then a Postdoctoral Fellow with the Centre for Telecommunications Studies, PUC-RIO, in 2005, and with the Signal Processing Laboratory, UFRJ, from 2005 to 2006. Since 2006, he has been with the Communications Group, Department of Electronics, University of York, York, U.K., where he is currently a Professor. Since 2013, he has also been a Professor with PUC-RIO. His research interests include communications and signal processing, areas in which he has published nearly 400 papers in international journals and conferences. He has participated in numerous projects funded by government agencies and industrial companies. He received a number of awards for his research work and has served as the General Chair of the IEEE 7th International Symposium on Wireless Communication Systems 2010, held in York, in 2010, as the Technical Programme Chair of ISWCS 2013 and WSA 2015, Ilmenau, Germany, and as the General Chair of the 9th IEEE Sensor Array and Multichannel Signal Processing Workshop, Rio de Janeiro, in 2016. He is an elected member of the IEEE Signal Processing Theory and Method Technical Committee. He currently serves as an Editor for the IEEE Transactions on Communications and the IEEE Wireless Communications Letters, and as a Senior Area Editor for the IEEE Signal Processing Letters.

• • •