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Space shift keying for multi-hop multi-branch networks

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ABSTRACT

In this paper, we propose two different multi-hop multiple-input multiple-output (MIMO) space shift keying (SSK) schemes and investigate their error performance. In the first scheme, we consider a multi-hop multi-branch SSK system, in which the source and destination are equipped with multiple transmit and receive antennas, respectively. In this scheme, SSK is applied by using the source transmit antennas. Moreover, in each branch, single-antenna relays are used to amplify the transmitted signal from the source and forward it to the next relay until it reaches to the destination. In the second scheme, we consider a multi-hop MIMO-SSK system with path selection. In this scheme, the best path is selected among multiple branches and a multiple-antenna source communicates with a multiple-antenna destination via the relays of the selected path. Each relay is equipped with multiple transmit and receive antennas. Moreover, the source and all relays employ SSK modulation to transmit information bits and each relay in each path follows the decode-and-forward protocol. Approximate theoretical error probability expressions are derived for both schemes. Furthermore, an asymptotic symbol error probability performance analysis is also performed for the multi-hop MIMO-SSK system with path selection. It is shown that the proposed multi-hop SSK systems outperform conventional multi-hop M-PSK systems in terms of the error performance for especially high data rates and sufficient number of receive antennas at the receiving nodes.

1. Introduction

High data rates and improved error performance can be obtained by using multiple-input multiple-output (MIMO) systems at the expense of using multiple radio-frequency (RF) chains at the transmitter, which increase the inter-channel interference (ICI) and the transceiver complexity as well as require synchronization among the transmit antennas. These challenges have led researchers to seek new solutions for the next generation MIMO systems [1]. In this context, novel single-RF MIMO techniques namely spatial modulation (SM) and space shift keying (SSK) have been proposed [2]. In SM and SSK, depending on the one-to-one mapping between the information bits and transmit antenna indices, typically only one transmit antenna is activated in a transmission interval and the other antennas remain turned off. Therefore, SM and SSK entirely avoid ICI, require no inter-antenna synchronization (IAS) among the transmit antennas and reduce the transceiver complexity. SSK is a special case of SM, which further decreases the transceiver complexity since it can be implemented with a very simple hardware that does not require I/Q modulation as well as employment of a RF chain [2–4].

Cooperative communications improves the transmission reliability and extends the coverage of wireless networks. Moreover, the effect of fading in wireless channels can be efficiently mitigated by the cooperative networks [5–10]. Due to their satisfactory error performance and low complexity, many researchers have studied SM and SSK in cooperative networks [11–21]. A dual-hop amplify-and-forward (AF) relaying scheme with SSK modulation has been studied in [11]. Furthermore, a cooperative decode-and-forward (DF) relaying scheme with SM has been investigated in [12]. A cooperative DF relaying scheme with SSK modulation, which considers the decoding errors at the relays, has been proposed in [13]. SSK aided AF and DF relaying with relay selection have been investigated in [14] and [15], respectively. In [16], the performance of SSK modulation with source transmit antenna selection and multiple DF relays has been investigated. In [17], a distributed SM protocol, in which the index of the relay conveys information, has been proposed. An AF relaying-aided cooperative space–time SSK scheme has been proposed in [18]. A cooperative AF-MIMO relaying scheme combining SSK with the best and the partial relay selection has been proposed in [19]. Moreover, in [20], DF-MIMO relaying scheme, in which all the nodes are equipped with multiple transmit and/or receive antennas, has been studied. The outage probability of both classical SM and cooperative SM systems has been investigated in [21].

On the other hand, employing multiple relays between source and destination enables the division of long links into multiple

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shorter links and long distance communications can be provided by multi-hop networks via hopping through relaying nodes. This improves the error performance, extends battery life, and provides broader and cheaper coverage [22–25]. Furthermore, in multi-hop multi-branch networks, transmitted signal from the source reaches to the destination via multiple cooperative multi-hop branches and therefore, D receives different copies of the transmitted signal. Hence, in addition to the advantages of multi-hop relaying, cooperative diversity is also achieved in multi-branch schemes [26–29]. Multi-hop relaying has been studied in many standards, including LTE Release-10, IEEE 802.11s, IEEE 802.15.5, IEEE 802.16, IEEE 802.16e, IEEE 802.16j and IEEE 802.20, and it finds many applications in wireless, sensor and vehicular ad hoc networks, cellular networks as well as Internet of Things applications [30–32]. However, to the best of author's knowledge, available studies on SM/SSK with multi-hop multi-branch networks are considerably limited. In the comprehensive study of [33], the performance of SSK modulation in multi-hop diversity and multi-hop multi-branch networks with DF relays have been investigated.

Motivated by all of the above, in this paper, we propose two new MIMO-SSK schemes, one of them employing AF and the other one employing DF relaying, in multi-hop networks and aim to utilize the benefits of SSK modulation in multi-hop networks and obtain diversity gain by using multiple branches and receive antennas. The novel contributions of this paper can be summarized as follows:

1. A novel multi-hop multi-branch MIMO-SSK scheme is proposed. In this scheme, S and D are equipped with multiple transmit and receive antennas, respectively and SSK is applied only at S. Single-antenna fixed-gain AF relays are employed in each branch of this scheme. The major contributions and important results for the proposed system can be listed as follows:
    - We derive a considerably accurate lower-bound expression for the pairwise error probability (PEP) of multi-hop single-branch transmission and an approximate expression for the average bit error probability (BEP) of multi-hop multi-branch transmission. The derived expressions are shown to become consistent with computer simulation results.
    - More importantly, numerical results demonstrate that the proposed SSK system outperforms the classical single-input multiple-output (SIMO) M-PSK system employing fixed-gain AF relaying for especially high data rates and sufficient number of receive antennas at D.
2. A novel multi-hop multi-branch MIMO-SSK scheme with multiple transmit and receive-antenna relays is proposed. In this scheme, S and D are equipped with multiple antennas as well and SSK is applied at S and all of the relays. Note that our system model differs from that of [33] in the following aspects: First, we consider the error propagation in multi-hop DF relaying. Second, a path is selected among available branches and transmission occurs via the selected path instead of activating all of the branches. Our system model is inspired by the path selection schemes of [28] and [29] in which multi-hop DF protocol is adopted. The major contributions and important results for the proposed system can be listed as follows:
    - Unlike [28] and [29], in which the performance for conventional M-PSK modulation have been studied, we consider the SSK modulation in each transmitting node and derive a closed-form approximate symbol error probability (SEP) expression for SSK modulation. The derived approximate SEP expression is shown to become considerably accurate for especially high signal-to-noise ratio (SNR) region.
    - More importantly, numerical results show that the proposed multi-hop SSK system with path selection outperforms the conventional multi-hop M-PSK system with path selection [28,29] in terms of the SEP performance for especially high data rates and sufficient number of receive antennas at the receiving nodes.
3. Unlike [28] and [29], our first scheme is a more general MIMO scheme with arbitrary number of receive antennas. Within this perspective, our first scheme has a simpler structure with AF processing and single-antenna relays, while the second scheme is a more sophisticated one with multi-antenna relays.
4. The proposed SSK systems completely avoid ICI, eliminate the requirement of IAS in a multi-hop network and can be implemented with a very simple hardware that does not require I/Q modulation as well as the employment of an RF chain. It has been shown via computer simulations that our analytical results are considerably consistent with the simulation results.

Notation: Bold capital letters denote matrices, whereas bold lowercase letters denote vectors. $\mathrm{E}[\cdot]$, $Q(\cdot)$ and $G[\cdot]$ stand for the expectation operator, the Gaussian Q function [34, (26.2.3)] and the Meijer's G-function [34, (9.301)], respectively. $P(\cdot)$ denotes the probability of an event. $(\cdot)^H$, $|\cdot|$, $\|\cdot\|$ and $\mathrm{Re}\{\cdot\}$ denote Hermitian transposition, the absolute value, the Frobenius norm operation and the real part operator, respectively. Moreover, $\mathcal{CN}(\mu, \sigma^2)$ denotes complex normal distribution, where μ and σ^2 stand for the mean and variance of the distribution, respectively.

2. Space shift keying for multi-hop multi-branch AF relaying

2.1. System model

We consider a multi-hop system employing AF relaying with L parallel cooperative branches between the source (S) and the destination (D), as shown in Fig. 1. There are K_p $(1 \le p \le L)$ single-antenna fixed-gain AF relays in the pth branch. Furthermore, S and D are equipped with N_t and N_r transmit and receive antennas, respectively. We denote the m_pth relay in the pth branch by R_{p,m_p} $\left(1 \le m_p \le K_p\right)$. At S, due to its low complexity and good performance [3], the SSK technique is applied by using N_t antennas. We assume that perfect channel state information (CSI) is available at the receiving nodes for the proposed scheme. The performance analysis in the presence of channel estimation errors is beyond the scope of this paper. However, it is shown that cooperative networks [35] and SSK modulation [36] are quite robust to imperfect CSI. It is also assumed that coordination among the relays allows for accurate symbol-level timing synchronization at D and orthogonal channel allocation as in many studies such as [5,23–29]. However, the issue of how exactly the synchronization between relays is performed is beyond the scope of our study. Finally, all channel coefficients are assumed to follow complex Gaussian distribution with zero-mean and unit variance as in many studies [5].

At the first stage of the transmission, a group of information bits is mapped to the index of the transmit antenna at S. Therefore, only a single transmit antenna is activated at S with the transmitted energy of E_S. S transmits the SSK symbol to the first relay nodes of parallel branches using the activated antenna. Each relay in each branch amplifies its received signal and forwards it to the next relay of the same branch until it reaches D. Hence, D receives L