Space Shift Keying Transmission for Intervehicular Communications

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***Abstract*—In this paper, we investigate the performance of space shift keying (SSK) transmission over a generalized multiple scattering channel. This channel model provides a realistic statistical description of an intervehicular communication environment and includes as special cases the Rician, Rayleigh, and double-Rayleigh channels. We derive an accurate closed form expression for the pairwise error probability of SSK, which is used to obtain the uncoded and coded error rate performances of SSK over various propagation scenarios. An asymptotic analysis for high values of signal-to-noise ratio is carried out to determine the diversity and coding gains of the proposed system. The performance analysis reveals the impact of the number of receive antennas and the use of soft and hard decision decoding on the error rate performance of SSK transmission over multiple scattering channels. Various numerically evaluated results accompanied by Monte Carlo simulations are presented to demonstrate the correctness of the proposed analysis.**

***Index Terms*—Intervehicular communication, multiple scattering, space shift keying, spatial modulation.**

I. Introduction

Intelligent transportation systems (ITSs) have received growing attention by the scientific community and the industry over the past several years because they promise to advance transportation safety and efficiency through the dissemination of road and traffic information [1]–[3]. The safety-related and information-related applications include messages regarding collisions, incidents, congestion, weather conditions, and coordination of vehicles at critical points such as blind crossings and highway entries. An integral part of ITSs are the so called intervehicular communication systems (IVCs) that include vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communications. In a IVC system, vehicles form mobile ad-hoc networks and communicate with each other to get real time information, thus enabling the driver to access information that is hard to acquire by on-board sensors.

In order to provide an accurate analysis for the performance of IVCs, we need to use appropriate statistical models for the fading channel. It is noted that experimental results and theoretical analysis reveal that statistical models such as Rayleigh or Rician fading may not apply to IVCs where both the transmitter and the receiver are in motion. A physically motivated model for fading channels is the so called second order scattering (SOS) radio propagation channel [4]. This model actually represents a special case of the multiple scattering model that was initially proposed in [5], [6] and was statistically analyzed in [7]. The main idea of the SOS model is that depending upon the distance between the transmitter and the receiver, one or more groups of scatterers participate in the propagation [5]. Thus, as it is also noted in [5] and [8], it is more likely that a mixture of single Rayleigh, double Rayleigh and line of sight (LoS) components will exist at the receiver side. Moreover, the SOS distribution has been verified in experimental studies that collected measurements in various mobile-to-mobile communication environments [9], [10].

In order to enhance system reliability in IVC environments, multiple-input multiple-output (MIMO) systems have been proposed in the literature [11], despite the fact that current wireless transmission technologies for V2V communication systems (e.g., 802.11p, WAVE) employ single antennas at the transmitter and receiver side. MIMO systems can configure a multiple antenna array in multiple modes, depending on the interference intensity, surrounding propagation environment or the vehicular application of interest, in order to meet stringent user requirements. Furthermore, MIMO can best exploit the highly dynamic nature of the V2V channel to increase the link range, improve the reliability of communication, increase the throughput of the network, and manage multiuser interference. Thus, MIMO systems clearly improve the quality of service in V2V communication systems.

However, despite the benefits that MIMO systems offer, they also result in an increase on the system complexity and cost. In order to alleviate the negative aspects of MIMO systems, a new modulation concept has been recently proposed, termed as spatial modulation (SM) [12]. This scheme aims at reducing the complexity and/or cost of multiple-antenna communications systems without affecting the end-to-end performance [13]–[15]. An important case of SM is the so-called space shift keying (SSK) modulation [16], [17], which employs multiple transmit antennas with only one transmitting at each time instant. According to SSK, the incoming bitstream is encoded into the index of the unique antenna which is switched on for transmission at each time instant while the others are switched off.

SSK can be considered as an ideal candidate for IVC systems, since it can improve system performance while minimizing transceiver complexity and cost. More specifically, SSK entirely avoids inter-channel interference (ICI) and inter-antenna synchronization (IAS), and only requires a single radio frequency (RF) chain at the transmitter, which is of critical

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importance for the small-sized vehicle mounted transmission systems. Moreover, the receiver design is inherently simpler compared to other multiple antenna systems, e.g., V-BLAST, since complicated ICI cancelation algorithms are not required. Furthermore, with the advent of multiple antennas technologies incorporated on vehicles, it is envisaged that transmission technologies such as SSK can be efficiently used in ITS systems for safety devices communications, ad hoc peer-to-peer networks and V2V communications [18], [19].

Because of the above mentioned advantages of SSK over other more conventional transmission schemes, it is important to investigate the potential performance improvements obtained by incorporating SSK in ITS systems. However, to the best of the the authors knowledge, this research topic has not been thoroughly investigated. In fact, only recently, there have been papers published in the open technical literature dealing with the performance analysis of V2V systems employing SM, e.g. see [20]. Specifically, in [20], the performance of SM over a three-dimensional V2V MIMO channel was investigated. Nevertheless, the potential enhancements of SSK on improving the performance of V2V and V2I systems in a multiple scattering environment still remains an open research topic which, to the best of our knowledge, has not been addressed so far in the open technical literature and thus motivates this work.

The main contributions of this paper can be summarized as follows:

- New analytical expressions for the average bit error probability (ABEP) of SSK operating over multiple scattering conditions are derived. When the transmitter is equipped with two antennas the resulting analytical expressions are exact, whereas for an arbitrary number of transmit apertures tight upper bounds are obtained;
- An asymptotic ABEP analysis is carried out, which reveals useful insights on the impact of system parameters on the attained error rate performance;
- Error performance bounds for coded SSK systems are derived using the transfer function technique and the performance improvements using hard and soft decision decoding are investigated;

The remainder of this paper is structured as follows. Section II outlines the system and channel models. In Section III, analytical expressions for the ABEP of uncoded SSK in multiple scattering environments are presented. The performance of coded SSK IVC systems is discussed in Section IV. In Section V various performance results and their interpretations are presented. Finally, concluding remarks are given in Section VI.

Mathematical notations: $\jmath = \sqrt{-1}$, $|\cdot|$ is the magnitude of a complex number, $\Gamma(\cdot)$ is the gamma function [21, Eq. (8.310/1)], $\mathbb{E}\langle\cdot\rangle$ denotes expectation, $J_a(\cdot)$ is the Bessel function of the first kind and order a [21, Eq. (8.402)], $Q(x) = 1/\sqrt{2\pi}\int_x^\infty \exp(-t^2/2)\mathrm{d}t$ is the Gaussian Q-function, and $\mathrm{Ei}(\cdot)$ the exponential integral function [21, Eq. (8.21)]. The probability density function (PDF) of the random variable (RV) X is denoted as $f_X(\cdot)$ and its corresponding moment generating function (MGF) as $\mathcal{M}_X(\cdot)$.

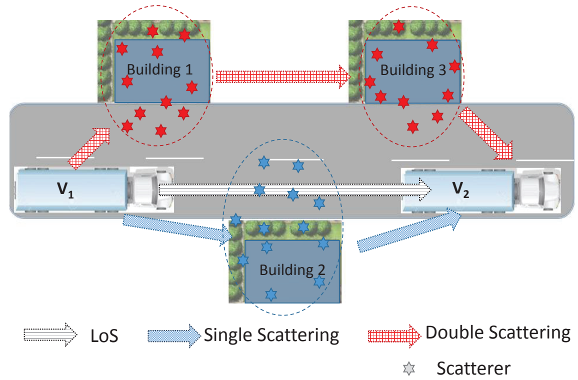

Fig. 1. Intervehicular communication scenario in SOS conditions.

II. System and Channel Model

A. System Model

We consider a generic IVC system, where both vehicles are in motion and with the local scattering environments as depicted in Fig. 1. We assume that the source vehicle employs N_t transmit antennas and the destination vehicle has N_r receive antennas. According to [13], the transmitter encodes blocks of $\log_2(N_t)$ data bits into the index of a single transmit antenna, t_i, for $i = 1, \ldots, N_t$. Such a block of bits is hereafter referred to as "message". It is assumed that the N_t messages are transmitted by the encoder with equal probability. During each time slot, the t_i-th antenna is switched on for data transmission while all other antennas are kept silent, i.e., $N_t - 1$ antennas do not transmit. At the receiver, a N_t hypothesis detection problem is solved to retrieve the active transmit antenna index, which results in the estimation of the unique sequence of bits emitted by the transmitter.

B. Channel Model

Depending on the propagation characteristics around the communicating vehicles, a variety of vehicular environments are often distinguished in the literature, such as highways, rural roads, suburban and urban streets. This variety of environments will result in different propagation conditions, which can be modeled by a weighted combination of LoS, single scattering and double scattering fading. In this work, the SOS distribution is adopted to model signal fluctuations, because this distribution can accurately approximate small-scale fading statistics for a wide range of IVC scenarios. Specifically, depending upon the existence or not of a LoS component as well as the distance between the transmitter and the receiver several communication scenarios exist where SOS conditions may arise. In Fig. 1, an example of a communication scenario is depicted, where SOS conditions exist under the assumption of a LoS path. For this scenario, a vehicle denoted as V_1 is moving in a straight road and communicating with another vehicle V_2. It is assumed that due to surrounding buildings and objects, three scattering clusters exist. More specifically, a part of the electromagnetic energy transmitted by V_1 is scattered by the cluster surrounding Building 1. Each scatterer in this cluster also scatters some energy to the cluster surrounding Building 2 and the remaining energy is received by vehicle V_2.

Scattering also occurs from cluster surrounding Building 3 and the resulting energy is received by V_2. The resulting channel transfer function is therefore affected by two components, the first modeled as a product of two Rayleigh random variables (RVs), i.e. it follows the so-called double-Rayleigh distribution, and the remainder modeled as a single Rayleigh RV. In addition to the scattering, there is a strongly dominant signal along a LoS between V_1 and V_2. Hereafter, it is also assumed that underlying channel is quasi-static, which is well justified for vehicular communication scenarios in rush-hour traffic. This is common assumption that has been widely adopted by many researchers in order to analyze the system performance, e.g., [22].

The transmitted signal can be expressed as a linear combination of signal components with constant, Rayleigh and double-Rayleigh distributed amplitudes. This multiple scattering model yields as special cases the Rician, Rayleigh, and double-Rayleigh fading channels. The complex channel gains $\alpha_{i,\ell}$, $\forall i = 1, 2, \ldots, N_t$ and $\ell = 1, 2, \ldots, N_r$ are defined as $\alpha_{i,\ell} = a_{i,\ell} \exp(\jmath\phi_{i,\ell})$ where $a_{i,\ell}$ and $\phi_{i,\ell}$ are the envelopes and phases of the link from the i-th transmit antenna to the ℓ-th receive antenna, respectively.

Under the considered multiple scattering scenario, $\alpha_{i,\ell}$ can be expressed as [7]

$$\begin{aligned}\alpha_{i,\ell} &= w_{0,i,\ell}\exp(\jmath\theta_{i,\ell}) + w_{1,i,\ell}H_{1,i,\ell} \\ &+ w_{2,i,\ell}H_{2,i,\ell}H_{3,i,\ell} = \sum_{n=0}^{2} C_{n,i,\ell}\end{aligned} \tag{1}$$

where $C_{0,i,\ell} = w_{0,i,\ell}\exp(\jmath\theta_{i,\ell})$ is the LoS component with constant magnitude and uniformly distributed phase over $[0, 2\pi)$, $C_{1,i,\ell} = w_{1,i,\ell}H_{1,i,\ell}$, $C_2 = w_{2,i,\ell}H_{2,i,\ell}H_{3,i,\ell}$ where $H_{n,i,\ell}$ are independent and identically distributed (i.i.d.) isotropic Gaussian processes having zero mean and unit variance, and $\{w_{n,i,\ell}\}_{n=0}^{2}$ are nonnegative real-valued constants that determine the mixture weights of the multiple scattering components.

III. Average Bit Error Probability of Uncoded SSK

A tight upper bound for the ABEP of SSK can be obtained from [16, Eq. (35)], as

$$\overline{P} \leq \frac{N_t^{-1}}{\log_2(N_t)} \sum_{t_1=1}^{N_t} \sum_{t_2 \neq t_1 = 1}^{N_t} N_b(t_1, t_2)\mathrm{PEP}_{\mathrm{SSK}}(t_1 \to t_2) \tag{2}$$

where $N_b(t_1, t_2)$ is the number of bit errors having occurred when the receiver decides that antenna t_2 instead of antenna t_1 has been active and $\mathrm{PEP}_{\mathrm{SSK}}(t_1 \to t_2)$ denotes the average pairwise error probability (PEP) related to the pair of transmit antennas t_1 and t_2, $\forall t_1, t_2 = 1, 2, \ldots, N_t$, defined as

$$\begin{aligned}\mathrm{PEP}_{\mathrm{SSK}}(t_1 \to t_2) &= \mathbb{E}\left\langle Q\left(\sqrt{\overline{\gamma}\sum_{\ell=1}^{N_r} Z_{\ell,t_1,t_2}}\right)\right\rangle \\ &= \frac{1}{\pi}\int_0^{\pi/2}\prod_{\ell=1}^{N_r}\mathcal{M}_{Z_{\ell,t_1,t_2}}\left(\frac{\overline{\gamma}}{2\sin^2\theta}\right)\mathrm{d}\theta\end{aligned} \tag{3}$$

where $\overline{\gamma} = E_m/(4N_0)$ is the signal-to-noise ratio (SNR) with E_m being the average energy transmitted by each antenna that emits a nonzero signal, N_0 is the variance of the additive white Gaussian noise (AWGN) and $Z_{\ell,t_1,t_2} = |a_{t_2,\ell}\exp(\jmath\phi_{t_2,\ell}) - a_{t_1,\ell}\exp(\jmath\phi_{t_1,\ell})|^2$. When two transmit antennas are used, i.e., when $N_t = 2$, the ABEP of SSK is equal to $\mathrm{PEP}_{\mathrm{SSK}}(t_1 \to t_2)$.

Using the tight approximation for the Gaussian Q-function presented in [23, Eq. (14)] (i.e., $Q(x) \approx \frac{1}{12}e^{-x^2} + \frac{1}{4}e^{-\frac{2x^2}{3}}$) as well as the definition of the MGF of a random variable X (i.e. $\mathcal{M}_X(s) = \mathbb{E}\langle\exp(-s\,X)\rangle$), an expression accurately approximating (3) can be deduced as

$$\begin{aligned}\mathrm{PEP}_{\mathrm{SSK}}(t_1 \to t_2) \approx \frac{1}{12}\prod_{\ell=1}^{N_r}\mathcal{M}_{Z_{\ell,t_1,t_2}}(\overline{\gamma}) \\ + \frac{1}{4}\prod_{\ell=1}^{N_r}\mathcal{M}_{Z_{\ell,t_1,t_2}}\left(\frac{2\overline{\gamma}}{3}\right).\end{aligned} \tag{4}$$

In the following analysis, analytical expressions for the MGF of Z_ℓ will be derived. By employing [24, Eq. (9)], $\mathcal{M}_{Z_{\ell,t_1,t_2}}(s)$ can be expressed as

$$\mathcal{M}_{Z_{\ell,t_1,t_2}}(s) = \frac{1}{2s}\int_0^\infty Re^{-\frac{R^2}{4s}}\Phi_{\alpha_{t_2,\ell}}(R)\Phi_{\alpha_{t_1,\ell}}(R)\mathrm{d}R \tag{5}$$

where $\Phi_{\alpha_{t_i,\ell}}(R) \triangleq \int_0^\infty J_0(Rr)f_{\alpha_{t_i,\ell}}(r)\mathrm{d}r$ is the zeroth order Hankel transform of $f_{\alpha_{t_i,\ell}}(r)/r$. Due to the independence of $C_{n,i,\ell}$, $\forall n \in \{0, 1, 2\}$, the Hankel transforms in (5) can be expressed as [7, Eq. (6)]

$$\Phi_{\alpha_{t_i,\ell}}(R) = \prod_{n=0}^{2}\Phi_{C_{n,t_i,\ell}}(R) \tag{6}$$

where $\Phi_{C_{n,t_i,\ell}}(R)$ are given as [7, Eqs. (8), (12), (13)]

$$\Phi_{C_{0,t_i,\ell}}(R) = J_0(w_{0,t_i,\ell}R) \tag{7a}$$

$$\Phi_{C_{1,t_i,\ell}}(R) = \exp\left(-w_{1,t_i,\ell}^2R^2/4\right) \tag{7b}$$

$$\Phi_{C_{2,t_i,\ell}}(R) = \frac{4}{4 + w_{2,t_i,\ell}^2R^2}. \tag{7c}$$

When a LoS component is present, i.e. $w_{0,t_i,\ell} \neq 0$, a closed form expression for $\mathcal{M}_{Z_{\ell,t_1,t_2}}(s)$ is very difficult - if not impossible - to be deduced and one has to resort to numerical integration. Assuming the absence of the LoS component, i.e., $w_{0,t_i,\ell} = 0$, it will be shown that $\mathcal{M}_{Z_{\ell,t_1,t_2}}(s)$ can be expressed in closed form. Such an assumption corresponds to a blind bend propagation environment for V2I communications as shown in Fig. 2 [8]. For this scenario, a vehicle moving along a curved street communicates with a fixed road-side unit (RSU) deployed on the other side of the curved road. The RSU, which acts as a fixed receiver, provides the driver with information related to traffic and road conditions. Due to the curvature of the street, the driver is not able to see the road ahead and thus the LoS component can be ignored. It is noted that this model does not consider higher-order scattering terms since first- and second-order components bear more energy than higher order components. Thus, by omitting higher-order components, the resulting channel model is considerably

$$\mathcal{M}_{Z_{\ell,t_1,t_2}}(s) = \frac{-\exp\left(\frac{1+w_{1,t_1,\ell}^2 s+w_{2,t_1,\ell}^2 s}{w_{1,t_2,\ell}^2 s}\right)\mathrm{Ei}(-\frac{1+w_{1,t_1,\ell}^2 s+w_{2,t_1,\ell}^2 s}{w_{1,t_2,\ell}^2 s}) + \exp(\frac{1+w_{1,t_1,\ell}^2 s+w_{2,t_1,\ell}^2 s}{w_{2,t_2,\ell}^2 s})\mathrm{Ei}(-\frac{1+w_{1,t_1,\ell}^2 s+w_{2,t_1,\ell}^2 s}{w_{2,t_2,\ell}^2 s})}{s(w_{1,t_2,\ell}^2 - w_{2,t_2,\ell}^2)} \tag{9}$$

$$c_\ell = \frac{-\exp\left(\frac{w_{1,t_1,\ell}^2+w_{2,t_1,\ell}^2}{w_{1,t_2,\ell}^2}\right)\mathrm{Ei}(-\frac{w_{1,t_1,\ell}^2+w_{2,t_1,\ell}^2}{w_{1,t_2,\ell}^2}) + \exp(\frac{w_{1,t_1,\ell}^2+w_{1,t_2,\ell}^2}{w_{2,t_2,\ell}^2})\mathrm{Ei}(-\frac{w_{1,t_1,\ell}^2+w_{2,t_1,\ell}^2 s}{w_{2,t_2,\ell}^2})}{w_{1,t_2,\ell}^2 - w_{2,t_2,\ell}^2} \tag{12}$$

Fig. 2. A blind bend propagation scenario for V2I communications

simplified without significant accuracy loss [8]. It is also pointed out that measurement campaigns presented in [25], [26] have confirmed that models that take into account single- and double-scattering components can accurately model fading over vehicular environments.

In this case, by substituting (7b) and (7c) into (5), $\mathcal{M}_{Z_{\ell,t_1,t_2}}(s)$ can be expressed as

$$\mathcal{M}_{Z_{\ell,t_1,t_2}}(s) = \frac{1}{2s}\int_0^\infty \frac{Re^{-\frac{(w_{1,t_1,\ell}^2+w_{1,t_2,\ell}^2+s^{-1})R^2}{4}}}{\left(1+\frac{R^2 w_{2,t_1,\ell}^2}{4}\right)\left(1+\frac{R^2 w_{2,t_2,\ell}^2}{4}\right)}\mathrm{d}R. \tag{8}$$

By performing the change of variables $R^2 = t$ along with a partial fraction decomposition and by employing [21, Eq. (3.354/4)], $\mathcal{M}_{Z_{\ell,t_1,t_2}}(s)$ can be deduced as (9) (shown at the top of this page).

In order to provide further insight on the impact of system parameters to the error rate performance, an asymptotic analysis at high values of $\overline{\gamma}$ is carried out. The diversity gain of the considered SSK system can be obtained using the approach presented in [27]. In particular, a generic analytical expression, which becomes asymptotically tight at high SNR values, can be derived for the average PEP appearing in (3), as follows:

$$\mathrm{PEP}_{\mathrm{SSK}}(t_1\to t_2) \overset{\overline{\gamma}\gg 1}{\approx} \frac{2^{N_r-1}\Gamma\left(N_r+\frac{1}{2}\right)}{\sqrt{\pi}\Gamma\left(N_r+1\right)}\left[\prod_{\ell=1}^{N_r} c_\ell\right]\overline{\gamma}^{-N_r} \tag{10}$$

where

$$c_\ell = \frac{1}{4}\int_0^\infty \prod_{i=1}^{2}\Phi_{\alpha_{t_i,\ell}}(\sqrt{y})\mathrm{d}y. \tag{11}$$

As it is evident, the diversity gain of SSK is equal to the number of receiving antennas, N_r. Assuming the absence of the LoS component, it can be shown that c_ℓ can be expressed in closed form. By performing a partial fraction decomposition and by employing [21, Eq. (3.354/4)], c_ℓ can be deduced as (12) (shown at the top of this page).

IV. Average Bit Error Probability of Coded SSK

When coded SSK is employed, the input signal is first encoded by a convolutional encoder. The encoded data are interleaved by a random block interleaver and transmitted through the wireless channel using SSK modulation. It is assumed that perfect interleaving at the transmitter and de-interleaving at the receiver is used. At the receiver, hard or soft decision decoding are considered.

For hard decision decoding, a union bound on the ABEP, P_{ub}, can be obtained as [28, Eqs. (8.2.27-8.2.30)]

$$\bar{P}_{\mathrm{ub}} \le \sum_{k=d_{\mathrm{free}}}^{\infty} c_k Z_k \tag{13}$$

where d_{free} is the free distance of the code,

$$Z_k = \begin{cases} \sum_{e=(k+1)/2}^{k}\binom{k}{k/e}p^e(1-p)^{k-e}, & k \text{ odd} \\ \frac{1}{2}\binom{k}{k/2}p^{k/2}(1-p)^{k/2} \\ +\sum_{e=(k/2)+1}^{k}\binom{k}{k/e}p^e(1-p)^{k-e}, & k \text{ even} \end{cases} \tag{14}$$

where

$$p = \frac{1}{\log_2(N_t)}\sum_{t_1=1}^{N_t}\sum_{t_2\neq t_1=1}^{N_t} N_b(t_1,t_2)\mathrm{PEP}_{\mathrm{SSK}}(t_1\to t_2) \tag{15}$$

and c_k are weight coefficients that can be obtained from the transfer function of the convolutional code, $T(D,N)$, as

$$\left.\frac{\partial T(D,N)}{\partial N}\right|_{N=1} = \sum_{k=d_{\mathrm{free}}}^{\infty} c_k D^k. \tag{16}$$

In (16), N is an indicator variable taking into account the number of the erroneous bits and D depends on the underlying PEP expression.

Considering maximum likelihood soft decision decoding, the log likelihood ratios (LLRs) for the i-th constellation bit, when the ℓ-th transmitting antenna is active, are computed as [28]

$$\begin{aligned}\mathrm{LLR} &= \log\frac{\Pr\{\ell^i=1|\mathbf{y}\}}{\Pr\{\ell^i=0|\mathbf{y}\}} \\ &= \log\frac{\sum_{\hat{\ell}\in\mathcal{L}_1^i}\exp\left(-\|\,\mathbf{y}-\mathbf{h}_{\hat{\ell}}s_\ell\,\|^2/N_0\right)}{\sum_{\hat{\ell}\in\mathcal{L}_0^i}\exp\left(-\|\,\mathbf{y}-\mathbf{h}_{\hat{\ell}}s_\ell\,\|^2/N_0\right)}\end{aligned} \tag{17}$$

where $\mathcal{L} \in \{1 : N_t\}$ is the set of spatial constellation points, $\mathcal{L}_1^i$ and $\mathcal{L}_0^i$ are subsets from $\mathcal{L}$ containing the transmitter indices having "1" and "0" at the i-th bit, respectively. The resulting data are finally decoded by a Viterbi decoder.

A union bound on the ABEP of the considered coded communication system can be obtained by employing a Chernoff bound on the Gaussian Q-function, i.e. $Q(x) \leq \exp(-x^2/2)$ as [28, Eq. (8.2.27)]

$$\bar{P}_{\text{ub}} \leq \left.\frac{\partial T(D,N)}{\partial N}\right|_{N=1, D=q} \tag{18}$$

where

$$q = \begin{cases} \prod_{\ell=1}^{N_r} \mathcal{M}_{Z_{\ell,t_1,t_2}}\left(\frac{\overline{\gamma}}{2}\right), & N_t = 2 \\ \prod_{t_1=1}^{N_t} \prod_{t_2 \neq t_1 = 1}^{N_t} \mathcal{M}_{Z_{\ell,t_1,t_2}}\left(\frac{\overline{\gamma}}{2}\right), & N_t > 2. \end{cases} \tag{19}$$

V. Numerical Results

In this section, we present various performance results obtained by numerically evaluating the mathematical expressions derived in Sections III and IV for uncoded and coded SSK systems, respectively, operating over multiple scattering environments. Figs. 3 and 4 depict the ABEP of uncoded SSK as a function of the SNR for $2 \times N_r$ SSK systems (obtained using (4) with (5) or (9)). For the uncoded schemes, in order to validate the accuracy of the derived expressions, complementary performance results obtained by means of Monte Carlo simulations are also included in these figures. For coded SSK systems, upper bounds of the ABEP versus SNR have been obtained for both hard and soft decision decoding, using (13) with (14) and, (18) with (19), respectively. The corresponding results are depicted in Fig. 5.

The IVC scenarios that were used to obtain the above performance graphs include a V2I scenario and a V2V scenario. In the V2I scenario, the source vehicle is equipped with $N_t = 2$ transmit antennas and moves in a curved road (no LoS component exists), whereas the RSU is equipped with $N_r \geq 1$ antennas. In the V2V scenario, the source vehicle is equipped with $N_t = 2$ transmit antennas whereas the destination vehicle has $N_r \geq 1$ receive antennas operating in a multiple scattering environment with a LoS component. Unless otherwise stated, for the V2V scenario, the weight coefficients are selected as $w_{0,t_1,\ell} = 1.5$, $w_{0,t_2,\ell} = 1$, $w_{1,t_1,\ell} = 1$, $w_{1,t_2,\ell} = \sqrt{2}$, $w_{2,t_1,\ell} = 1.2$, $w_{2,t_2,\ell} = 2\sqrt{2}$. As already mentioned, for the V2I scenario $w_{0,t_1,\ell} = w_{0,t_2,\ell} = 0$, whereas the remaining weights are the same with the V2V scenario.

In Fig. 3, the derived ABEP approximation using (4) with (9) for the V2I scenario with non LoS component is illustrated as a function of $\overline{\gamma}$, using different values of N_r. The exact ABEP is also evaluated using Monte-Carlo simulations and it is included as a reference (illustrated by square patterns). It is observed from Fig. 3 that the derived ABEP provides a very tight approximation for the entire SNR region. For all cases considered, it is observed that the asymptotic analysis correctly predicts the diversity gain of the SSK transmission scheme and that the asymptotic ABEP coincides with the exact one in the high SNR regime.

In Fig. 4, the derived ABEP approximation for the V2V scenario is illustrated as a function of $\overline{\gamma}$, using different values

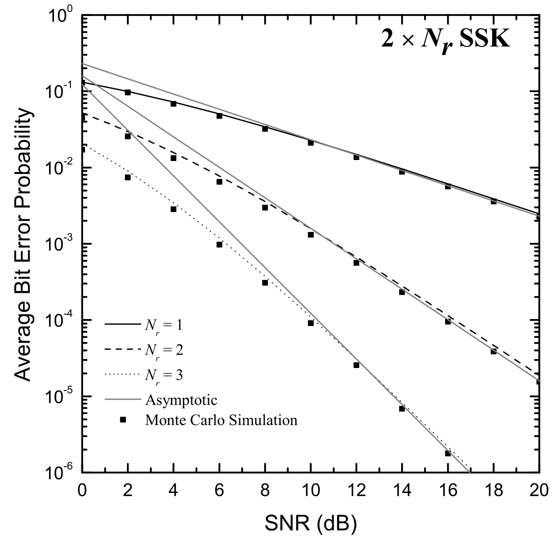

Fig. 3. ABEP of uncoded SSK in a V2I environment with curved road.

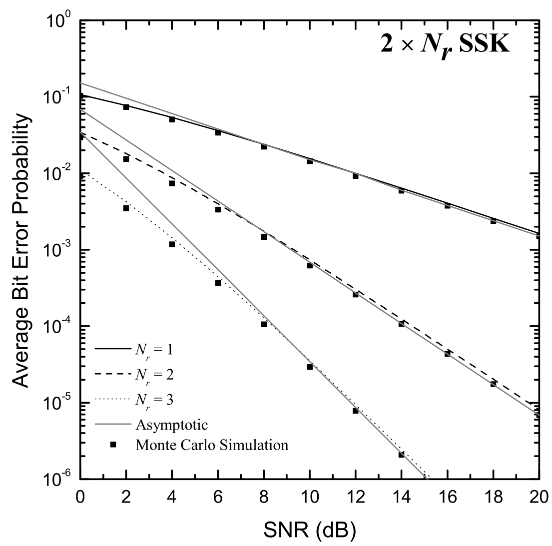

Fig. 4. ABEP of uncoded SSK in a V2V environment with LoS conditions.

of N_r. Since a closed-form expression for the ABEP in (4) cannot be derived in this case, all results have been evaluated using numerical integration of (5). This integration can be performed in an efficient and accurate manner by means of numerical integration techniques available in mathematical software packages such as Matlab or Mathematica [1]. As far as the accuracy of the exact and asymptotic analysis is concerned, we observe similar findings to those reported for the V2I case.

Next, a coded SSK system employing a rate 1/2 convolutional encoder is considered. The transfer function of the code is given by [28]

$$T(D,N) = \frac{ND^5}{1 - 2ND} = \sum_{k=5}^{\infty} 2^{k-5} N^{k-4} D^k. \tag{20}$$

It is evident that the free distance of this code is $d_{\text{free}} = 5$. Based on the infinite series representation of the transfer function in (20), upper bounds on the ABEP for hard decoded

[1] In this work the standard build-in function **NIntegrate[]** available in Mathematica was utilized to numerically integrate (5).

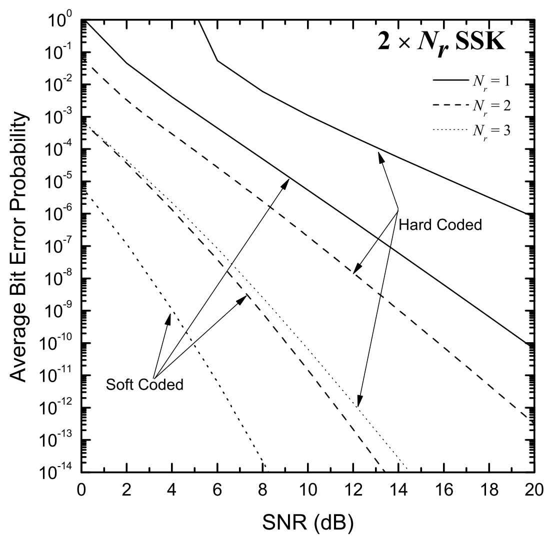

Fig. 5. ABEP bounds of coded SSK in a V2I environment with curved road.

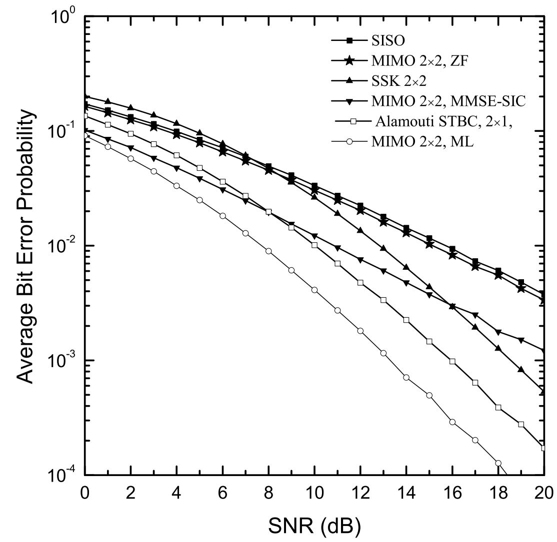

Fig. 6. ABEP of multiple antenna schemes in a V2I environment with curved road.

SSK systems can be readily evaluated. Moreover, substituting (9) to (19), a union bound on the ABEP for soft decoded SSK systems can be readily deduced from (18). Fig. 5 shows the upper bounds of the ABEP for convolutionally coded SSK systems using both hard and soft decision decoding. It is shown, that the incorporation of convolutional coding significantly improves the performance of SSK systems, even when a small number of receive antennas is employed. Specifically, when three receiving antennas are employed, i.e. when $N_r = 3$, the proposed system configuration achieves an ABEP of 10^{-14} at 14.2 dB and 8 dB for hard and soft decoded systems, respectively.

Finally, in Fig. 6 the performance of SSK with $N_r = N_t = 2$ antennas in a V2I scenario is compared with the performance of several well-established MIMO schemes with binary phase shift keying modulation (BPSK), such as i) MIMO 2×2 with zero-force (ZF) equalizer, ii) MIMO 2×2 with minimum mean square error (MMSE) equalizer and successive interference cancellation (SIC), iii) MIMO with ML detection and iv) space time block codes (STBC) based on the Alamouti scheme with $N_t = 2$ and $N_r = 1$ [29], [30]. As a reference, the performance of the SISO scheme is also depicted in the same figure. The corresponding weights are set to $w_{1,t_i,\ell} = 1/2$, $w_{1,t_i,\ell} = \sqrt{3}/2$, $\forall i = 1, 2, \ldots, N_t$. Since in this case $w_{1,t_2,\ell}$ = $w_{2,t_2,\ell}$, $\mathcal{M}_{Z_{\ell,t_1,t_2}}(s)$ was evaluated by numerically integrating (8). As it can be observed, SSK outperforms SISO and MIMO with ZF for medium and high SNR values. Moreover, it even outperforms MIMO with MMSE-SIC at the high SNR regime. However, SSK performs worse than STBC and MIMO with ML. Nevertheless, this disadvantage is compensated by its significant lower hardware requirements and signal processing complexity compared to these MIMO schemes.

VI. Concluding Remarks

In this paper, we introduced SSK transmission for IVC operating over a multiple scattering channel model, which can be used to model various propagation scenarios. Analytical expressions for uncoded and coded SSK transmissions over this fading model were derived for the first time. An asymptotic analysis for high SNR values was carried out to obtain the achieved diversity gain of the SSK MIMO system. For the coded system, we used the transfer function technique associated with the newly derived PEP expression for the multiple scattering channel, to obtain upper bounds of the ABEP performance for both hard and soft decision decoding. Our analytical expressions offer a simple and reliable method to estimate ABEP performance of SSK systems in multiple scattering channel models without resorting to lengthy simulations. Therefore, they are useful for the development, design, and test of future V2V and V2I communication systems. Finally, of particular interest is the application of the proposed transmission scheme when time varying channel models are considered, which is left for future contribution.

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