Coherent Versus Non-Coherent Reconfigurable Antenna Aided Virtual MIMO Systems

Shinya Sugiura, *Senior Member, IEEE*

***Abstract*—In this letter, motivated by the recent universal encoding concept of space-time shift keying (STSK), we propose a novel single radio-frequency (RF) based virtual multiple-input multiple-output (VMIMO) architecture, employing a pattern reconfigurable antenna at a transmitter. More specifically, the proposed scheme is based on the concept of pattern-time dispersion matrix activation, which is capable of striking a flexible balance between the transmission rate and the diversity gain, while enabling symbol-based low-complexity detection. Furthermore, we conceive its non-coherently detected counterpart in order to dispense with any channel estimation as well as additional pilot overhead, hence having the potential of outperforming the conventional coherently-detected VMIMO schemes in many practical scenarios.**

***Index Terms*—Noncoherent detection, reconfigurable antenna, single-RF MIMO, space-time shift keying, spatial modulation.**

I. Introduction

ALTHOUGH using co-located antenna arrays both at a transmitter and a receiver substantially improves the achievable performance of wireless communication links [1], [2], it is quite a challenging task to install multiple uncorrelated antenna elements in a small mobile handset. To this end, the concept of cooperative communications [3] was invented, where a collection of nodes, each having a single antenna element, act as a virtual antenna array. Such a distributed antenna arrangement benefits from virtual multiple-input multiple-output (VMIMO) channels, while avoiding installation of multiple antenna elements and the associated radio frequency (RF) circuits at each cooperating node. On the other hand, the cooperative diversity gain may be achieved at the expense of substantial additional overhead, which is required for negotiation of the nodes as well as timing and frequency synchronization. Additionally, it is also hard for a fast-moving destination receiver to accurately estimate all the related channel coefficients, i.e. those of the source-relay, source-destination and relay-destination links.

Manuscript received November 21, 2013; revised January 16, 2014; accepted January 27, 2014. Date of publication January 29, 2014; date of current version February 06, 2014. This work was supported in part by the Strategic Information and Communications R & D Promotion Programme (SCOPE) of the Ministry of Internal Affairs and Communications, Japan. The associate editor coordinating the review of this manuscript and approving it for publication was Prof. Zoltan Safar.

The author is with the Department of Computer and Information Sciences, Tokyo University of Agriculture and Technology, Tokyo, 184-8588, Japan (e-mail: sugiura@ieee.org).

Digital Object Identifier 10.1109/LSP.2014.2303471

In contrast to the aforementioned cooperation-based VMIMO approach, another VMIMO approach was developed in [4], [5], where a single-RF reconfigurable antenna is employed at the transmitter. More specifically, the use of a single-RF reconfigurable antenna, capable of switching/forming multiple antenna patterns [6], [7], contributes to the creation of VMIMO channels without relying on any cooperation with other nodes. Note, on the other hand, that this single-RF structure does not support simultaneous multiple symbol transmissions, unlike the classic MIMO transmitters. For example, Kalis *et al.* [4] presented the idea of mapping diverse bit-streams onto an orthogonal basis, which is defined in the beam-space domain of the reconfigurable antenna. Here, activating a single out of multiple preassigned antenna patterns conveys information bits, assuming that each channel coefficient is accurately acquired at the receiver. Furthermore in [5], the set of basis functions was extended to include arbitrary $\mathcal{M}$-ary phase-shift keying (PSK) modulation schemes, in order to increase the transmission rate. Unfortunately, a single-RF VMIMO transmitter has to repetitively send multiple pilot symbols, each corresponding to the specific antenna pattern, while classic multiple-RF MIMO systems are capable of simultaneous transmissions.

In the context of co-located MIMO systems, in [8] the universal space-time encoding concept of space-time shift keying (STSK) was proposed, which is conceived for utilizing both the space- and time-dimensions. This is enabled by the philosophy of space-time dispersion-matrix activation, rather than antenna activation. As a beneficial result, the STSK scheme is capable of striking a flexible balance between the rate and the diversity gains, although the STSK transmitter typically assumes the employment of multiple-RF branches.

Against this background, the novel contributions of this letter are as follows. Motivated by the recent space-time encoding concept of STSK [8], we propose a novel single-RF reconfigurable VMIMO transmission scheme, which is capable of striking a flexible rate-versus-diversity tradeoff, hence outperforming classic VMIMO schemes. As the extension of our reconfigurable VMIMO scheme exploiting coherent detection, we further introduce its non-coherent detection-based counterpart, which uses differential encoding of unitary pattern-time codewords. The proposed non-coherent scheme is capable of dispensing with any channel state information (CSI) estimation at the receiver, while the conventional reconfigurable VMIMO schemes [4], [5] typically rely on pilot-based CSI estimation, which imposes the aforementioned reduced-efficiency repetitive pilot transmissions. The non-coherent VMIMO scheme retains the fundamental benefits of the coherent one, although the corresponding non-coherent receiver suffers from the

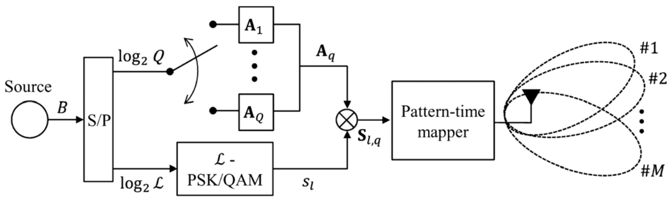

Fig. 1. Transmitter structure of our coherently-detected reconfigurable VMIMO scheme.

well-known performance loss compared to its coherent counterpart. Note that the proposed single-RF VMIMO transmitter does not require multiple RF chains, while its receiver counterpart is imposed by the requirement of multiple RF chains in order to attain the receive diversity gain. In this sense, the proposed scheme may be viewed as a *semi virtual* MIMO system.

II. System Model

A. Transmitter Structure

Fig. 1 portrays the transmitter structure of our coherently-detected reconfigurable VMIMO scheme, which is equipped with a single-RF pattern-reconfigurable antenna element. Here, it is assumed for simplicity that M number of antenna patterns are preassigned before the commence of transmissions and one out of them is activated during each symbol interval. Additionally, throughout this letter we consider open-loop VMIMO scenarios, where no feedback information is available at the transmitter.

Let us define a two-dimensional pattern-time matrix $\mathbf{S}_{l,q} \in \mathbb{C}^{M\times T}$ as follows: $\mathbf{S}_{l,q} = s_l \mathbf{A}_q \in \mathbb{C}^{M\times T}$, where $\mathbf{A}_q \in \mathbb{C}^{M\times T}(q = 1, \cdots, Q)$ represents a set of dispersion matrices, while $s_l(l = 1, \cdots, \mathcal{L})$ are the classic complex-valued constellations and Q is the number of dispersion matrices. Consider that $B = \log_2 Q + \log_2 \mathcal{L}$ information bits are input to our transmitter per block duration, i.e. T symbol durations. The B input bits are then serial-to-parallel (S/P) converted to $B_1 = \log_2 Q$ and $B_2 = \log_2 \mathcal{L}$ bits. Here, the $B_1 = \log_2 Q$ bits are used to activate one out of Q dispersion matrices $\mathbf{A}_q$, while the $B_2 = \log_2 \mathcal{L}$ bits are modulated to a symbol s_l. Finally, the two-dimensional codeword $\mathbf{S}_{l,q}$ is generated. Importantly, in each dispersion matrix $\mathbf{A}_q$ there is only a single non-zero element per column. This constraint enables us to avoid simultaneously transmitting multiple symbols at each symbol duration. Additionally, in order to maintain the average transmission power per block to be unity, we impose the following power constraint $\mathrm{tr}[\mathbf{A}_q\mathbf{A}_q^H] = T(q = 1, \cdots, Q)$, where tr $[\cdot]$ is the trace of a matrix. In order to elaborate a little further, codeword $\mathbf{S}_{l,q}$ represents an index set (l, q), where q is mapped by a set of T activated patterns and their complex-valued coefficients $(a_{q1}, \cdots, a_{qT})$, while l is modulated to a constellation point. Hence, it can be interpreted that our encoding concept is based on two different modulation schemes, namely pattern-time activation as well as the classic modulation scheme. Moreover, since the legitimate number of codewords $\mathbf{S}_{l,q}$ is $\mathcal{L} \cdot Q$, the transmission rate R of our scheme is given by $R = \log_2(\mathcal{L} \cdot Q)/T$. This implies that upon increasing the number of dispersion matrices Q or the constellation size $\mathcal{L}$, the normalized transmission rate logarithmically increases.

Since the achievable performance of our reconfigurable VMIMO scheme is characterized by a set of dispersion matrices $\mathbf{A}_q(q = 1, \cdots, Q)$, its optimization is an important issue. So far, several design criteria have been proposed for the dispersion-matrix optimization of STSK and linear dispersion codes (LDCs) [9]. Representative examples include the criteria of coding-gain maximization [2], pairwise-error probability (PEP) minimization and capacity-maximization [8], [9]. These conventional approaches are directly applicable to optimizing our reconfigurable VMIMO scheme's dispersion-matrix set.

B. Detection Algorithm

In this letter, we consider the optimal maximum likelihood (ML) detector at the receiver. Firstly, the block-based received signals may be expressed as $\mathbf{Y} = \mathbf{H}\mathbf{S}_{l,q} + \mathbf{V} \in \mathbb{C}^{N\times T}$, where $\mathbf{H} \in \mathbb{C}^{N\times M}$ represents the channel matrix and N denotes the number of receive antennas. Here, the nth-row and mth-column element of $\mathbf{H}$ denotes the complex-valued channel envelope between the mth transmit antenna pattern and the nth receive antenna element. Furthermore, $\mathbf{V} \in \mathbb{C}^{N\times T}$ represents the corresponding additive noise components, each obeying a circularly-symmetric complex-valued Gaussian distribution of $\mathcal{CN}(0, N_0)$, having zero mean and noise variance N_0. Here, let us assume that the channel coefficients $\mathbf{H}$ and the noise variance N_0 are accurately estimated at the receiver, although we will relax this assumption by introducing our scheme's non-coherent counterpart in Section III.

Moreover, by stacking received signals $\mathbf{Y}$, the block-based signal model may be transformed to its vectorial form as follows [8]: $\bar{\mathbf{Y}} = \bar{\mathbf{H}}\mathbf{K}_{l,q} + \bar{\mathbf{V}} \in \mathbb{C}^{NT\times 1}$, where we have $\bar{\mathbf{Y}} = \vec{(\mathbf{Y})} \in \mathbb{C}^{NT\times 1}$, $\bar{\mathbf{H}} = (\mathbf{I} \otimes \mathbf{H})\chi \in \mathbb{C}^{NT\times Q}$, $\chi = [\vec{(\mathbf{A}_1)}, \cdots, \vec{(\mathbf{A}_Q)}] \in \mathbb{C}^{MT\times Q}$, $\bar{\mathbf{V}} = \vec{(\mathbf{V})} \in \mathbb{C}^{NT\times 1}$, and $\mathbf{K}_{l,q} = [0, \cdots, 0, s_l, 0, \cdots, 0]^T \in \mathbb{C}^{Q\times 1}$, while $\vec{(\cdot)}$ denotes the vectorial stacking operation and $\mathbf{I}$ is the identity matrix.

Then we arrive at the ML metric, which is represented by [8] $(\hat{l}, \hat{q}) = \arg\min_{\forall(l,q)} \|\bar{\mathbf{Y}} - \bar{\mathbf{H}}\mathbf{K}_{l,q}\|^2 = \arg\min_{\forall(l,q)} \|\bar{\mathbf{Y}} - s_l[\bar{\mathbf{H}}]_q\|^2$, where $(\hat{l}, \hat{q})$ denotes the estimated index set and $[\cdot]_q$ represents the qth column of a matrix. This ML criterion results in the optimal error-rate performance in uncoded scenarios. In order to reduce the ML scheme's decoding complexity, it is beneficial to employ the reduced-complexity detector of [10], which is not imposed by any performance penalty in comparison to the optimal ML detector.[1] Additionally, the maximum achievable diversity order $\mathcal{D}$ of the proposed scheme is given by $\mathcal{D} = N \cdot \min(M, T)$. Hence, unlike the conventional reconfigurable VMIMO schemes, our VMIMO arrangement is capable of striking a tradeoff between the rate and the diversity gain in a flexible manner, by appropriately designing the related system parameters of $(M, N, T, Q, \mathcal{L})$.

III. Non-Coherent Reconfigurable VMIMO Arrangements

In this section, we introduce a reconfigurable VMIMO scheme that uses non-coherent detection. The scheme, which is depicted in Fig. 2, allows us to eliminate the requirement

[1]More specifically, the two reduced-complexity detectors were proposed in [10]. The one is capable of attaining the optimal ML performance, while the other one exhibits a further complexity reduction at the sacrifice of a slight performance penalty in terms of the achievable error rate.

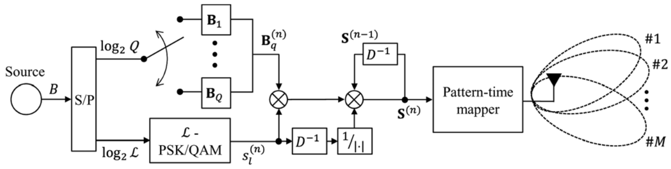

Fig. 2. Transmitter structure of our non-coherently detected reconfigurable VMIMO arrangement.

of any pilot overhead and receiver's CSI estimation. It is assumed for simplicity that the number of transmit antenna patterns M is equal to the number of symbol durations T per block. Furthermore, in comparison to the coherent reconfigurable VMIMO scheme of Section II-A, we further impose the unitary constraint on a set of the dispersion matrices $\mathbf{B}_q \in \mathbb{C}^{M\times T}$ $(q = 1,\cdots,Q)$, which leads to $\mathbf{B}_q\mathbf{B}_q^H = \mathbf{B}_q^H\mathbf{B}_q = \mathbf{I}$. In each block duration, B information bits are input and S/P converted to $B_1 = \log_2 Q$ and $B_2 = \log_2 \mathcal{L}$ bits. Then, according to the B_1 bits, one out of Q dispersion matrices is activated as $\mathbf{B}_q^{(n)}$, while the B_2 bits are mapped to a PSK/QAM symbol $s_l^{(n)}$, in a similar manner to our coherent VMIMO scheme of Section II-A. Here, the superscript n denotes the space-time block index. Finally, the transmitted pattern-time matrix $\mathbf{S}^{(n)}$ of the nth block may be formulated with the aid of differential encoding as follows:

$$\mathbf{S}^{(n)} = \frac{s_l^{(n)}}{\left|s_l^{(n-1)}\right|}\mathbf{S}^{(n-1)}\mathbf{B}_q^{(n)} \ (n \geq 1), \tag{1}$$

where we have $\mathbf{S}^{(0)} = \mathbf{I}$ and $|s_l^{(0)}| = 1$.

Assuming that the channel matrix $\mathbf{H}$ remains constant over two successive block intervals, the corresponding received signals at the $(n-1)$st and the nth blocks may be expressed as

$$\mathbf{Y}^{(n-1)} = \mathbf{H}\mathbf{S}^{(n-1)} + \mathbf{V}^{(n-1)}, \tag{2}$$

$$\mathbf{Y}^{(n)} = \mathbf{H}\mathbf{S}^{(n)} + \mathbf{V}^{(n)} \tag{3}$$

$$= \frac{s_l^{(n)}}{\left|s_l^{(n-1)}\right|}\mathbf{H}\mathbf{S}^{(n-1)}\mathbf{B}_q^{(n)} + \mathbf{V}^{(n)}. \tag{4}$$

From (1), (2) and (4),

$$\mathbf{Y}^{(n)} = \frac{s_l^{(n)}}{\left|s_l^{(n-1)}\right|}\mathbf{Y}^{(n-1)}\mathbf{B}_q^{(n)} + \mathbf{V}'^{(n)}, \tag{5}$$

where

$$\mathbf{V}'^{(n)} = \mathbf{V}^{(n)} - \frac{s_l^{(n)}}{\left|s_l^{(n-1)}\right|}\mathbf{V}^{(n-1)}\mathbf{B}_q^{(n)}. \tag{6}$$

Hence, the detection at the nth block interval may be represented by

$$(\hat{q},\hat{l}) = \arg\min_{(q,l)}\left|\mathbf{Y}^{(n)} - \frac{s_l^{(n)}}{\nu}\mathbf{Y}^{(n-1)}\mathbf{B}_q^{(n)}\right|^2, \tag{7}$$

where we assume that the estimate $\nu = |s_{\hat{l}}^{(n-1)}|$ is obtained from the detection result of the $(n-1)$st block. It can be predicted from (7) that mis-detection of a symbol $\nu = s_{\hat{l}}^{(n-1)}$ in the $(n-1)$st block may induce error propagation to the (l,q) index-set detection in the nth block. However, as demonstrated later in Section IV this effect can be maintained to be minimal, hence does not cause any substantial performance degradation. We also note that the detector formulated in (7) does not include any channel elements, hence dispensing with channel estimation. Since the variance of the equivalent noise components $\mathbf{V}'^{(n)}$, expressed by (6), is higher than that of the original ones $\mathbf{V}^{(n)}$, our non-coherent scheme suffers from the well-known performance penalty, which is typically imposed by differentially encoding scheme. Furthermore, the detection expressed by (6) is not the optimal ML detector, since the equivalent noise components $\mathbf{V}'^{(n)}$ are non-Gaussian [2].

For example, a dispersion-matrix set of our non-coherent reconfigurable VMIMO scheme, having the parameters of $(M,T,Q) = (4,4,4)$, may be given by

$$\mathbf{B}_1 = \begin{bmatrix} 0 & 0 & 0 & b_{14} \\ 0 & 0 & b_{13} & 0 \\ 0 & b_{12} & 0 & 0 \\ b_{11} & 0 & 0 & 0 \end{bmatrix}, \tag{8}$$

$$\mathbf{B}_2 = \begin{bmatrix} 0 & 0 & b_{23} & 0 \\ 0 & b_{22} & 0 & 0 \\ b_{21} & 0 & 0 & 0 \\ 0 & 0 & 0 & b_{24} \end{bmatrix}, \tag{9}$$

$$\mathbf{B}_3 = \begin{bmatrix} b_{31} & 0 & 0 & 0 \\ 0 & 0 & 0 & b_{34} \\ 0 & 0 & b_{33} & 0 \\ 0 & b_{32} & 0 & 0 \end{bmatrix}, \tag{10}$$

$$\mathbf{B}_4 = \begin{bmatrix} 0 & b_{42} & 0 & 0 \\ b_{41} & 0 & 0 & 0 \\ 0 & 0 & 0 & b_{44} \\ 0 & 0 & b_{43} & 0 \end{bmatrix}, \tag{11}$$

which are imposed by the power constraints of $|b_{qm}| = 1 (1 \leq q, m \leq 4)$. The above-mentioned dispersion matrix structure of (8)–(11) guarantees that the differentially-encoded codeword $\mathbf{S}^{(n)}$ of (5) retains the sparse structure, having only one non-zero element in each column, hence ensuring single-symbol transmission at each time duration.

Again, it should be stressed that our non-coherently detected VMIMO scheme proposed in this section has the useful advantages over the conventional coherent-detection based schemes. To be more specific, in the conventional single-RF MIMO schemes, such as the reconfigurable VMIMO schemes [4], [5], pilot symbols associated with all the transmit antenna elements/patterns have to be periodically transmitted. The situation becomes significantly severe for a rapidly changing topology of vehicles traveling at high velocities, where more frequent pilot insertions are required for accurate CSI estimation. In this sense, the non-coherent detection is especially beneficial in the context of single-RF VMIMO schemes.

The decoding complexity of this non-coherent VMIMO detector is nearly identical to those of the proposed coherent VMIMO scheme as well as the conventional co-located STSK scheme [8]. Nevertheless, considering that the absence of the need for channel estimation, the non-coherent receiver's complexity is relatively low in total. Furthermore, since both the two VMIMO schemes do not rely on symbol multiplexing, their decoding complexity is not as high as that of the classic spatial-multiplexing-based MIMO scheme. The detailed

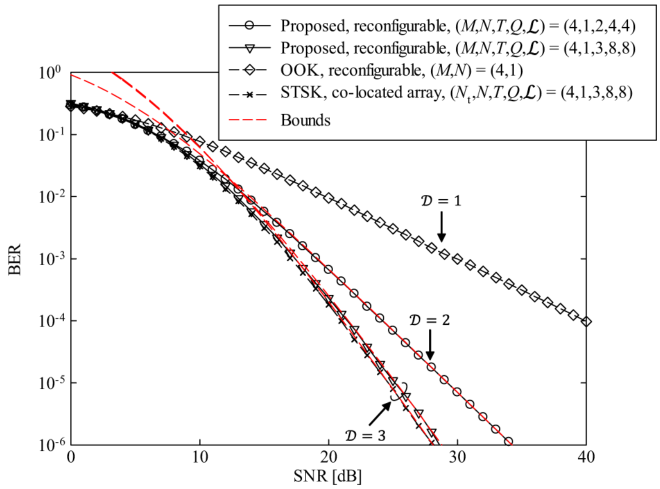

Fig. 3. Achievable BER performance of our coherent reconfigurable VMIMO schemes, employing the parameters of $(M,N,T,Q,\mathcal{L}) = (4,1,2,4,4)$ and (4,1,3,8,8), as well as of the conventional OOK-based reconfigurable VMIMO scheme, assuming uncorrelated Rayleigh fading channels. The normalized transmission rate of each scheme was given by 2 bits/symbol.

quantitative complexity evaluations of our VMIMO schemes basically follow that conduced in [10], [11].

IV. Simulation Results

In this section, we provide performance results in order to characterize the proposed reconfigurable VMIMO schemes. We considered $M = 4$ patterns preassigned to the transmit reconfigurable antenna, while the number of received antenna elements was set to $N = 1$ for simplicity. Furthermore, each dispersion-matrix set was optimized so as to maximize discrete-input continuous-output memoryless channel (DCMC) capacity [2] with the aid of the random search algorithm, according to [8].

Firstly, we considered the coherently-detected reconfigurable VMIMO arrangement of Section II-A, under the assumption of fast-block Rayleigh fading. In Fig. 3 we compared the achievable bit-error ratio (BER) curves of a set of reconfigurable VMIMO schemes, namely the proposed schemes of $(M,N,T,Q,\mathcal{L}) = (4,1,2,4,4)$ and $(M,N,T,Q,\mathcal{L}) = (4,1,3,8,8)$ as well as the on–off keying (OOK)-based scheme of $(M,N) = (4,1)$. Here, we also plotted the associated BER curve of the co-located antenna array system, namely the STSK scheme [8] of $(M,N,T,Q,\mathcal{L}) = (4,1,3,8,8)$. Note that the fundamental difference between the STSK and our reconfigurable VMIMO schemes is that the STSK scheme's dispersion matrix set is not imposed by sparse structure since a co-located antenna array is capable of simultaneous symbol transmissions from multiple antenna elements. This indicates that the achievable BER performance of our reconfigurable VMIMO scheme is lower bounded by that of co-located STSK scheme [8] in uncorrelated fading scenarios. Moreover, the red dash lines represents the theoretical tight upper bounds [12], which were plotted for the sake of validating our Monte Carlo simulations. It was found from Fig. 3 that according to our scheme's diversity order, the two proposed schemes achieved the maximum attainable diversity orders of two and three, hence each exhibiting a higher BER performance than that of the OOK-based benchmark. Additionally, the performance difference between the co-located STSK scheme and its reconfigurable VMIMO counterpart was found to be marginal, which showed that our sparse dispersion matrix structure did not induce any substantial performance degradation in this specific scenario.

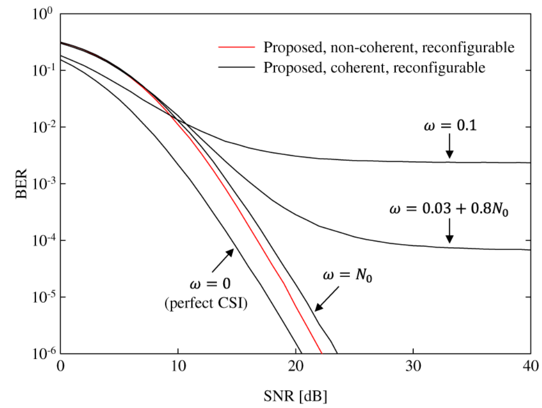

Fig. 4. Comparisons of achievable BER performance between our coherently and non-coherently detected reconfigurable VMIMO schemes, both employing system parameters $(M,N,T,Q,\mathcal{L}) = (4,1,4,4,4)$. The normalized transmission rate of each scheme was given by 1 bits/symbol.

Next, Fig. 4 compares the achievable BER performance between our coherently and non-coherently detected reconfigurable VMIMO schemes of Sections II and III, both employing system parameters $(M,N,T,Q,\mathcal{L}) = (4,1,4,4,4)$. The normalized transmission rate of each scheme was 1 bits/symbol. Here, we considered the effects of CSI estimation errors by defining the estimated channels $\hat{\mathbf{H}}$ as $\hat{\mathbf{H}} = \mathbf{H} + \Delta\mathbf{H} \in \mathbb{C}^{N \times M}$, where we have the additive CSI estimation-error components $\Delta\mathbf{H}$, each obeying the complex-valued random Gaussian distribution $\mathcal{CN}(0,\omega)$. In our simulation, the variance ω was given by $\omega = 0, N_0, 0.03 + 0.8N_0$ and 0.1. As shown in Fig. 4, the coherent scheme outperformed its non-coherent counterpart in the perfect CSI scenario, owing to the non-coherent scheme's noise-enhancement effects, imposed by the differential decoding process. However, upon introducing channel estimation errors to the coherent scheme's CSI estimation, the non-coherent scheme exhibited a performance advantage over the coherent scheme. It should also be noted that all the conventional reconfigurable VMIMO schemes as well as the single-RF antenna-switching schemes suffer from the same CSI-estimation error related problems.

V. Conclusions

In this letter, we proposed novel coherent and non-coherent reconfigurable VMIMO architectures, using a single-RF reconfigurable antenna element at the transmitter. Our novel encoding concept, i.e. pattern-time dispersion matrix activation, allows us to strike a flexible rate-versus-diversity tradeoff, hence having the potential of outperforming the conventional reconfigurable VMIMO schemes, while enabling low-complexity symbol-based detection.

Acknowledgment

The author gratefully acknowledges the support of the Strategic Information and Communications R & D Promotion Programme (SCOPE) of the Ministry of Internal Affairs and Communications.

REFERENCES

[1] V. Tarokh, N. Seshadri, and A. Calderbank, “Space-time codes for high data rate wireless communication: Performance criterion and code construction,” *IEEE Trans. Inf. Theory*, vol. 44, no. 2, pp. 744–765, 1998.

[2] L. Hanzo, O. Alamri, M. El-Hajjar, and N. Wu, *Near-Capacity Multi-Functional MIMO Systems: Sphere-Packing, Iterative Detection and Cooperation*. Piscataway, NJ, USA: Wiley-IEEE Press, 2009.

[3] J. Laneman and G. Wornell, “Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks,” *IEEE Trans. Inform. Theory*, vol. 49, no. 10, pp. 2415–2425, 2003.

[4] A. Kalis, A. Kanatas, and C. Papadias, “A novel approach to MIMO transmission using a single RF front end,” *IEEE J. Sel. Areas Commun.*, vol. 26, no. 6, pp. 972–980, 2008.

[5] O. Alrabadi, C. Papadias, A. Kalis, and R. Prasad, “A universal encoding scheme for MIMO transmission using a single active element for PSK modulation schemes,” *IEEE Trans. Wireless Commun.*, vol. 8, no. 10, pp. 5133–5142, 2009.

[6] R. Schlub, J. Lu, and T. Ohira, “Seven-element ground skirt monopole ESPAR antenna design from a genetic algorithm and the finite element method,” *IEEE Trans. Antennas Propagat.*, vol. 51, no. 11, pp. 3033–3039, Nov. 2003.

[7] S. Sugiura and H. Iizuka, “Reactively steered ring antenna array for automotive application,” *IEEE Trans. Antennas Propagat.*, vol. 55, no. 7, pp. 1902–1908, Jul. 2007.

[8] S. Sugiura, S. Chen, and L. Hanzo, “Coherent and differential space-time shift keying: A dispersion matrix approach,” *IEEE Trans. Commun.*, vol. 58, no. 11, pp. 3219–3230, Nov. 2010.

[9] B. Hassibi and B. Hochwald, “High-rate codes that are linear in space and time,” *IEEE Trans. Inf. Theory*, vol. 48, no. 7, pp. 1804–1824, 2002.

[10] S. Sugiura, C. Xu, S. X. Ng, and L. Hanzo, “Reduced-complexity coherent versus non-coherent QAM-aided space-time shift keying,” *IEEE Trans. Commun.*, vol. 59, no. 11, pp. 3090–3101, Nov. 2011.

[11] C. Xu, S. Sugiura, S. X. Ng, and L. Hanzo, “Spatial modulation and space-time shift keying: Optimal performance at a reduced detection complexity,” *IEEE Trans. Commun.*, vol. 61, no. 1, pp. 206–216, Jan. 2013.

[12] M. K. Simon and M. S. Alouini, *Digital Communication over Fading Channels*. Piscataway, NJ, USA: Wiley-IEEE Press, 2005.