Combination lock-like differential codebook for temporally correlated channels

Y.J. Kim, X. Li, T. Kim and D.J. Love

A novel differential codebook, preserving inherent properties of 3GPP long-term evolution (LTE) codebooks, is proposed for temporally correlated channels. The steady-state achievable throughput performance of the proposed codebook shows at least 0.9 dB of SNR better than that of the conventional LTE codebook with the same amount of feedback information.

Introduction: Long-term evolution (LTE) and LTE-Advanced (LTE-A) systems have adopted codebook-based transmit beamforming schemes to achieve a good trade-off between beamforming gain and the required amount of feedback information [1, 2]. When the codebook is designed in standards, it is generally assumed that the multiple input multiple output (MIMO) channel coefficients are independent at every time instant. However, in practice, temporal correlation between adjacent channel realisations often exists so that the consecutive precoders are likely to be similar. Some well-defined differential codebooks accounting the temporal correlation of the channel into the codebook design have been exploited and show robust performance [3, 4] (see more references in [2]). However, the properties of the conventional differential codebooks are far from those of LTE codebooks in terms of the complexity, nested property and constant modulus property. Thus, in this Letter, we propose a new differential codebook having LTE codebook properties.

We consider a limited feedback MIMO beamforming system with M_t transmit and M_r receive antennas. At the transmitter, a single data stream is transmitted. Both the transmitter and the receiver have a common codebook with $N = 2^B$ codewords, $\mathcal{W}_k = \{\boldsymbol{w}_k^1, \cdots, \boldsymbol{w}_k^N\}$ where k is the channel realisation index and $\boldsymbol{w}_k^n \in \mathbb{C}^{M_t \times 1}$, $n = 1, \cdots, N$ denotes the nth codeword in $\mathcal{W}_k$. Note that $\mathbb{C}^{a \times b}$ denotes a set of $a \times b$ complex matrices. According to the instantaneous channel estimate, the receiver selects its preferable codeword index, n_{opt}, and only the B bits of the chosen codeword index are sent back to the transmitter. Then the transmitter selects the beamforming vector $\boldsymbol{w}_k$ according to n_{opt} as $\boldsymbol{w}_k = \boldsymbol{w}_k^{n_{opt}}$. The M_r-dimensional received vector $\boldsymbol{y}_k$ is described by

$$\boldsymbol{y}_k = \sqrt{\rho}\boldsymbol{H}_k\boldsymbol{w}_k s_k + \boldsymbol{n}_k \tag{1}$$

where $\boldsymbol{H}_k \in \mathbb{C}^{M_r \times M_t}$ denotes the channel matrix at discrete time instant k with IID entries according to $\mathcal{CN}(0, 1)$, $\boldsymbol{n}_k \in \mathbb{C}^{M_r \times 1}$ denotes the additive white Gaussian noise (AWGN), and ρ represents the signal-to-noise ratio (SNR). For a temporally correlated channel, the channel evolution can be modelled by a first-order Gauss-Markov process:

$$\boldsymbol{H}_k = \epsilon\boldsymbol{H}_{k-1} + \sqrt{1+\epsilon^2}\boldsymbol{G}_k \tag{2}$$

where $\boldsymbol{G}_k \in \mathbb{C}^{M_r \times M_t}$ denotes the innovation process having IID entries with $\mathcal{CN}(0, 1)$. The time correlation coefficient $\epsilon (0 \le \epsilon \le 1)$ quantifies the amount of correlation between all the elements of the temporally adjacent channel matrices.

Combination lock-like differential codebook: The main focus of the previous work in [3, 4] is on developing statistical frameworks to track the channel directional variation. In these approaches, codebooks are found without constraints on the codeword alphabets. Given a restriction on the codeword alphabets, the explicit differential codebook design has not been well addressed as far as we understand in the literature. Therefore we propose an explicit differential codebook design methodology when available codeword alphabets (with unit modulus) are restricted to a finite set. Specifically, the proposed differential codebook, $\mathcal{W}_{diff} = \{\boldsymbol{w}^1, \cdots, \boldsymbol{w}^N\}$ where $\boldsymbol{w}^n \in \mathbb{C}^{M_t \times 1}$, $n = 1, \cdots, N$ denotes the nth codeword in the codebook, uses only 8-PSK constellations as its elements of codewords for utilising the benefits agreed in the standardisation meeting [1]. Under the above constraint, we choose the codebook $\mathcal{W}_{diff}$ having minimum spherical cap radius, which is centred at $\boldsymbol{w}^1$, using the criterion

$$\mathcal{W}_{diff} = \arg\min_{\widetilde{W}_{diff}} \delta(\widetilde{W}_{diff}) \tag{3}$$

where $\widetilde{W}_{diff}$ denotes the set of possible differential codebooks constrained from 8-PSK alphabets, $\delta(\widetilde{W}_{diff})$ is the maximum distance between $\boldsymbol{w}^1$ and a codeword in $\widetilde{W}_{diff}$, and all the elements of $\boldsymbol{w}^1$ consist of 1. Note that the distance function in (3) does not depend on the distance relations between the vectors in the set $\{\boldsymbol{w}^2, \cdots, \boldsymbol{w}^N\}$. Because we are limited to 8-PSK vector entries, $\boldsymbol{w}^2, \cdots, \boldsymbol{w}^N$ can be chosen based on simulation in the case when multiple codebooks minimise $\delta(\cdot)$. The distance in (3) is the chordal metric between $\boldsymbol{w}^1$ and $\boldsymbol{w}^j$, which is defined as

$$\frac{1}{\sqrt{2}}\|\boldsymbol{w}^1(\boldsymbol{w}^1)^H - \boldsymbol{w}^j(\boldsymbol{w}^j)^H\|F \tag{4}$$

where $j \neq 1$ is the index of all possible codewords having 8-PSK constellations. To illustrate the design method of the proposed differential codebook briefly, we consider that M_t is four. At first, $\boldsymbol{w}^1 = [1\ 1\ 1\ 1]^T$ is fixed, and the remaining $(N - 1)$ codewords are determined one by one among all possible codewords having 8-PSK elements, showing the least chordal distances from $\boldsymbol{w}^1$, as shown in Table 1.

Table 1: Proposed differential codebook

Index	Codeword	Index	Codeword
1	$[1\ 1\ 1\ 1]^T$	9	$[1\ e^{j\frac{\pi}{4}} e^{j\frac{\pi}{4}}\ 1\ ]^T$
2	$[1\ e^{j\frac{\pi}{4}}\ 1\ 1\ ]^T$	10	$[1\ 1\ e^{j\frac{\pi}{4}} e^{j\frac{\pi}{4}}\ 1\ ]^T$
3	$[1\ 1\ e^{j\frac{\pi}{4}}\ 1\ ]^T$	11	$[1\ e^{j\frac{\pi}{4}}\ 1\ e^{j\frac{\pi}{4}}\ 1\ ]^T$
4	$[1\ 1\ 1\ e^{j\frac{\pi}{4}}]^T$	12	$[1\ e^{j\frac{\pi}{4}} e^{j\frac{\pi}{4}} e^{j\frac{\pi}{4}}\ 1\ ]^T$
5	$[1\ e^{-j\frac{\pi}{4}}\ 1\ 1\ ]^T$	13	$[1\ e^{-j\frac{\pi}{4}} e^{-j\frac{\pi}{4}}\ 1\ ]^T$
6	$[1\ 1\ e^{-j\frac{\pi}{4}}\ 1\ ]^T$	14	$[1\ 1\ e^{-j\frac{\pi}{4}} e^{-j\frac{\pi}{4}}]^T$
7	$[1\ 1\ 1\ e^{-j\frac{\pi}{4}}]^T$	15	$[1\ e^{-j\frac{\pi}{4}}\ 1\ e^{-j\frac{\pi}{4}}]^T$
8	$[1\ e^{-j\frac{\pi}{4}}\ 1\ e^{j\frac{\pi}{4}}]^T$	16	$[1\ e^{-j\frac{\pi}{4}} e^{-j\frac{\pi}{4}} e^{-j\frac{\pi}{4}}]^T$

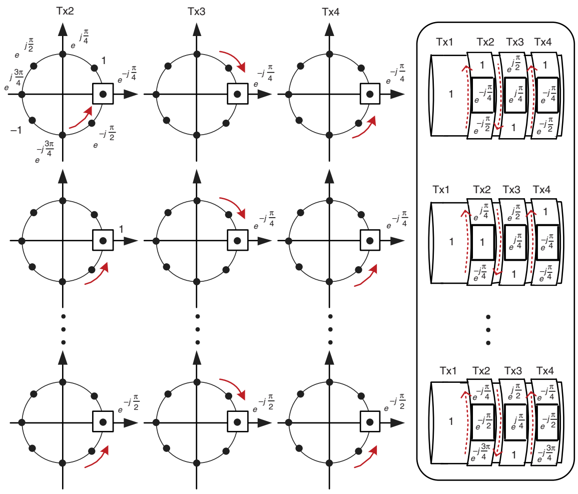

Fig. 1 *Codebook update example using $\mathcal{W}_{diff}$ in Table 1 when previous precoder is $\left[1 e^{-j\frac{\pi}{4}} e^{j\frac{\pi}{4}} e^{-j\frac{\pi}{4}}\right]^T$*

The transmitter and receiver compute the codebook update at time instant k by multiplying the differential codebook $\mathcal{W}_{diff}$ and the previous beamforming vector $\boldsymbol{w}_{k-1}^{n_{opt}}$, which is described by

$$\mathcal{W}_k = \langle \mathcal{W}_{diff} \times w_{k-1}^{n_{opt}} \rangle \tag{5}$$

where the operator $\langle \cdot \rangle$ in (5) extracts the set $\mathcal{W}_k$, in which the ith element of $\mathcal{W}_k$ is formulated as the Hadamard product of the ith element of $\mathcal{W}_{diff}$ and $\boldsymbol{w}_{k-1}^{n_{opt}}$. As the current codebook is updated at every time instant, the codewords in the codebook change continuously. The operation of the codebook update can be illustrated as a series of combination locks, each of which has a circular sequence of 8-PSK symbols. When the precoder of $\left[1 e^{-j\frac{\pi}{4}} e^{j\frac{\pi}{4}} e^{-j\frac{\pi}{4}}\right]^T$ is selected at the previous time instant, the operation of the codebook update can be shown as in Fig. 1. Finally, the optimum codeword index at time instant k is determined, which maximises the capacity as

$$n_{opt} = \arg\max_{1 \le i \le N} \log_2(1 + \rho\|\boldsymbol{H}_k\boldsymbol{w}_k^i\|_2^2) \tag{6}$$

Simulation results: Monte Carlo simulations were performed to illustrate the steady-state achievable throughput performance of the proposed differential codebook compared with existing schemes. Throughout the simulation, we assume $(M_t, M_r) = (4, 4)$ for exhibition of the results in Fig. 2. The codebook size N is fixed to 16, which is the same as in the LTE system. When we generate ϵ of a first-order Gauss-Markov process, 3 km/h velocity, $f_c = 2.5$ GHz, feedback interval of 5 ms, and an error-free feedback channel are assumed, where the typical temporal correlation coefficient is $\epsilon = 0.988$ [3]. The achievable throughput performance of the proposed codebook along with those of the ideal SVD codebook, differential rotation codebook without spherical cap radius adaptation in [3], quasi-diagonal codebook in [4], ideal equal gain transmission (EGT) codebook, and LTE release-9 codebook are shown in Fig. 2. Those curves are denoted with the legends of ideal SVD, codebook in [3], codebook in [4], ideal EGT and LTE, respectively. The proposed codebook shows 0.3 bit/s/Hz better performance than the LTE codebook when the SNR is fixed to 10 dB, and 0.9 dB SNR gain to obtain the same steady-state achievable throughput compared with the LTE codebook. Note that the proposed differential codebook with 8-PSK alphabets is a subset of the EGT codebook. As seen from Fig. 2, the achievable throughput of the proposed codebook almost approaches that of the ideal equal gain transmission. Moreover, as ϵ varies from 0.999 (1 km/h) to 0.872 (10 km/h), we can obtain similar simulation results.

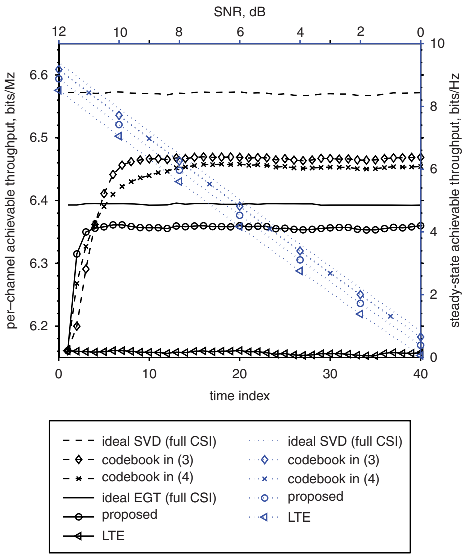

Fig. 2 *Per-time instance achievable throughput and steady-state achievable throughput performances of various differential codebook schemes when $(M_t, M_r) = (4, 4)$*

- - - ideal SVD (full SCI)
- ◇ - codebook in [3]
- × - codebook in [4]
—○— proposed
—◁— LTE

Conclusions: A simple combination lock-like differential feedback MIMO system for slowly fading channels has been investigated. Owing to having only 8-PSK constellations, the proposed codebook can be designed quickly and reduce the transceiver complexity greatly. From the simulation results, the proposed codebook shows significant throughput gain, preserving perfect compatibility with LTE and LTE-A systems.

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