Non-orthogonal multiple access without channel state information for similar channel conditions

Wenlong Xia✉, Qingdang Meng, Qingchuan Tao and Ray T. Chen

A downlink non-orthogonal multiple access with QPSK input constellations based on virtual channel optimisation is presented to address the similar channel conditions scenario. The novel idea is to construct a uniquely decodable sum constellation by maximising the minimum Euclidean distance among the points of the superposed constellation. An optimal angle difference is derived to make the proposed scheme easy to implement. With a fixed angle pair setup, a non-orthogonal multiple access system without the knowledge of channel state information is proposed. Simulation results are provided to demonstrate the performance of the proposed scheme.

Introduction: Non-orthogonal multiple access (NOMA) has been investigated intensively for the capability of massive connectivity and higher spectral efficiency compared with OMA [1, 2]. For power-domain NOMA, the typical paradigm is that users who employ the NOMA scheme at the transmitter are superposed in the power domain and successive interference cancellation (SIC) is conducted at the receivers. This SIC-based NOMA is based on the large channel path loss (power difference) among the users. However, this paradigm is impractical for some scenarios. For example, a centred base station (BS) with users uniformly distributed, the number of far users (weak users) is much more than that of the near users (strong users) since the peripheral zone of BS is larger than the centre zone. In this case, we can only pair part of weak users with strong users. Since channel gain differences among those far users are small [termed similar channel conditions (SCCs)], the unpaired weak users will resort to the conventional OMA such as time-division multiple access (TDMA) or frequency-DMA (FDMA). To address the SCCs scenario, network-coded multiple access NOMA is proposed in [3], which is rather high computational complexity. In [4], an MIMO-NOMA is reported. However, the proposed method artificially created a beamforming vector to increase one user's effective power gain while decreasing that of the other user. For an application such as serving cell-edge users, the power reduction will cause a big impact on the outage probability. Thus, this scheme cannot be applied to group two weak users.

The performance is marginal for SIC-based NOMA with SCCs. This is because only the power domain is considered. When the phases of user's signals are taken into consideration, the performance can be improved. In this Letter, we propose a virtual channel optimisation (VCO) method based on our prior work in [5] to address the SCCs scenario. The idea is to construct a uniquely decodable sum constellation [6, II-A] by optimising the phases of two users' signals and maximising the minimum Euclidean distance (MED) among the superposed points. We present that a determinate solution is obtained for QPSK modulation by solving the VCO problem. Then, we further argue that our proposed NOMA can be implemented without the channel state information (CSI) with the SCCs constraint.

System model: A model of two-user single-input–single-output downlink NOMA is considered. At the BS, two users' messages s_1 and s_2, each multiplying a virtual channel coefficient $w_k = A_k e^{j\theta_k}$ $(k = 1, 2)$, where A_k and θ_k are the amplitude and phase of w_k, respectively, are superposed and transmitted to two receivers. We assume that the average power for each user is $P_1 = P_2 = P$, which can be applied for serving cell-edge users, and the amplitude of each virtual channel is normalised. Then the superposed signal at the BS is given by

$$x = \sqrt{P} w_1 s_1 + \sqrt{P} w_2 s_2 = \sqrt{P} s_1 e^{j\theta_1} + \sqrt{P} s_2 e^{j\theta_2} \qquad (1)$$

where s_k is chosen from a finite-alphabet set with uniform distribution and $E[|s_k|^2] = 1$. The received signal of the kth user is

$$y_k = h_k x + z_k = h_k\left(\sqrt{P} s_1 e^{j\theta_1} + \sqrt{P} s_2 e^{j\theta_2}\right) + z_k \qquad (2)$$

where h_k is the complex Rayleigh fading channel for the user $k (k = 1, 2)$. For SCCs, we define the channel difference ratio $\beta = 10\lg(|h_2|^2/|h_1|^2)$ with the constraint $|\beta| \le \gamma$, where γ is a preset channel difference threshold. z_k is the additive circularly symmetric complex Gaussian noise with zero mean and variance σ_k^2, i.e. $z_k \sim \mathcal{CN}(0, \sigma_k^2)$. For simplicity, we assume $z_1 = z_2 = z$ and $\sigma_1^2 = \sigma_2^2 = \sigma^2 = WN_0$, where W is the bandwidth and N_0 is the power spectral density of the noise.

For SIC-based NOMA, a user with the strongest power is decoded first treating the other users with weaker power as noise, which requires the power difference to be large enough to avoid error propagation. However, for our SCCs model, SIC cannot separate the superposed signal properly due to the almost equivalent power level between the two users. Therefore, the maximum-likelihood (ML) detector is employed to decode the superposed signal. Unlike SIC which decodes signals successively, ML decodes the two users' signals in one time. Although the ML detector has high computational complexity, it is affordable with the evolution of hardware and parallel computing for lower-order modulation. Moreover, the ML detector has the advantage of low decoding latency at the cost of complexity compared with SIC.

For the two users' signals are finite input constellations in practise, we employ the sum constellation constrained capacity (CCC) to evaluate the performance of overall throughput for our scheme. The CCC value for each user with the ML decoder can be expressed as [6]

$$C_1(\theta_1, \theta_2, W) = \log_2(N_1) - \frac{1}{N_1 N_2}\sum_{n_1=1}^{N_1}\sum_{n_2=1}^{N_2} E\left[\log_2\left[f_1(\theta_1, \theta_2, W)\right]\right] \qquad (3)$$

$$C_2(\theta_1, \theta_2, W) = \log_2(N_2) - \frac{1}{N_1 N_2}\sum_{n_1=1}^{N_1}\sum_{n_2=1}^{N_2} E\left[\log_2\left[f_2(\theta_1, \theta_2, W)\right]\right] \qquad (4)$$

$$C_{\rm sum}(\theta_1, \theta_2, W) = C_1(\theta_1, \theta_2, W) + C_2(\theta_1, \theta_2, W) \qquad (5)$$

where

$$f_1(\theta_1, \theta_2, W) = \frac{\sum_{m_1=1}^{N_1}\sum_{m_2=1}^{N_2} \exp\left(-|h_1[d(s'_1, s'_2, n_1, n_2, m_1, m_2)] + z|^2/WN_0\right)}{\sum_{m_2=1}^{N_2} \exp\left(-\left|h_1\sqrt{P(s'_2(n_2) - s'_2(m_2))} + z\right|^2/WN_0\right)}$$

$$f_2(\theta_1, \theta_2, W) = \frac{\sum_{m_1=1}^{N_1}\sum_{m_2=1}^{N_2} \exp\left(-|h_2[d(s'_1, s'_2, n_1, n_2, m_1, m_2)] + z|^2/WN_0\right)}{\sum_{m_1=1}^{N_1} \exp\left(-\left|h_2\sqrt{P(s'_1(n_1) - s'_1(m_1))} + z\right|^2/WN_0\right)}$$

$d(s'_1, s'_2, n_1, n_2, m_1, m_2) = \sqrt{P}\left(s'_1(n_1) + s'_2(n_2) - s'_1(m_1) - s'_2(m_2)\right)$, $s'_1 = s_1 e^{j\theta_1}$, $s'_2 = s_2 e^{j\theta_1}$, $E(\cdot)$ is the expectation of a random variable, N_1 and N_2 are the size of two input constellations $\mathcal{S}_1$ and $\mathcal{S}_2$, respectively. $C_{\rm sum}(\theta_1, \theta_2, W)$ is the sum capacity of two users.

Algorithm design: For superposed symbols in conventional NOMA with the same power gain for two users as described in (1), the sum constellation may result in ambiguity due to the many-to-one mappings. For example, a pair of inputs with QPSK sets $(s_1, s_2) = \left(\exp(j\pi/4), \exp(-j3\pi/4)\right)$, and another input pair $(\hat{s}_1, \hat{s}_2) = \left(\exp(-j\pi/4), \exp(j3\pi/4)\right)$, $w_k = 1$ for conventional NOMA, then the two superposed points $x_1 = \sqrt{P}s_1 + \sqrt{P}s_2 = 0$ and $x_2 = \sqrt{P}\hat{s}_1 + \sqrt{P}\hat{s}_2 = 0$. So point 0 cannot be uniquely decoded at the receivers. However, we can construct a one-to-one mapping by introducing the virtual channel scheme. Note that $C_{\rm sum}(\theta_1, \theta_2, W)$ is a function of the distance distribution of two constellations. Then we can optimise θ_k to improve the sum capacity at a given W by maximising the MED between the two input constellations at the transmitter. For two superposed points $x_1 = \sqrt{P}(w_1 s_1 + w_2 s_2)$ and $x_2 = \sqrt{P}(w_1 \hat{s}_1 + w_2 \hat{s}_2)$, where $s_1, \hat{s}_1 \in \mathcal{S}_1$, $s_2, \hat{s}_2 \in \mathcal{S}_2$, and $(s_1, s_2) \neq (\hat{s}_1, \hat{s}_2)$, the squared Euclidean distance of two superposed points is

$$D^2(\theta_1, \theta_2) = P\left\{[\Re(x_1) - \Re(x_2)]^2 + [\Im(x_1) - \Im(x_2)]^2\right\} \qquad (6)$$

where $\Re(v)$ and $\Im(v)$ denote the real and imaginary parts of the variable v. For QPSK constellations, $N_1 = N_2 = 4$ and $\mathcal{S}_1 = \mathcal{S}_2 = \left\{\exp(j\varphi) | \varphi = \pm\pi/4, \pm 3\pi/4\right\}$, there are 16 superposed points and the total distance values have $16 \times 15 = 240$ elements. As many equal values exist, we can have 14 different distance elements which are listed in Table 1.

As can be seen from Table 1, the possible minimum distance can be chosen only from $P(4 - 4\sin\Delta\theta)$, $P(4 - 4\cos\Delta\theta)$, and $P(6 - 4\cos\Delta\theta - 4\sin\Delta\theta)$ for $\Delta\theta \in [0, 90°)$, where $\Delta\theta = \theta_1 - \theta_2$.

The distance distribution of these candidates with $P = 1$ is plotted in Fig. 1. The decoding performance is dominated by the MED at high signal-to-noise ratio (SNR) according to the nearest neighbour approximation in [7, ch5]. By maximising the MED, we can achieve optimal decoding performance. From Fig. 1, when $4 - 4\cos\Delta\theta = 6 - 4\cos\Delta\theta - 4\sin\Delta\theta$ or $4 - 4\sin\Delta\theta = 6 - 4\cos\Delta\theta - 4\sin\Delta\theta$, which corresponds to $\Delta\theta = 30°\,\text{or}\,60°$, the maximum MED is obtained. Considering the symmetry of QPSK constellation, we limit $\Delta\theta \in [0,\ 45°)$. Then we obtain a determinate solution for $\Delta\theta$ with the exact value of $\Delta\theta = 30°$.

Table 1: Squared distance values for QPSK signal sets, $\Delta\theta = \theta_1 - \theta_2$

No.	$D^2(\theta_1,\ \theta_2)$	Number of equal values
1	$2P$	64
2	$4P$	32
3	$P(4\cos\Delta\theta + 4)$	16
4	$P(4\sin\Delta\theta + 4)$	16
5	$P(4 - 4\sin\Delta\theta)$	16
6	$P(4 - 4\cos\Delta\theta)$	16
7	$P(6 + 4\cos\Delta\theta - 4\sin\Delta\theta)$	16
8	$P(6 + 4\cos\Delta\theta + 4\sin\Delta\theta)$	16
9	$P(6 + 4\sin\Delta\theta - 4\cos\Delta\theta)$	16
10	$P(6 - 4\cos\Delta\theta - 4\sin\Delta\theta)$	16
11	$P(8\cos\Delta\theta + 8)$	4
12	$P(8\sin\Delta\theta + 8)$	4
13	$P(8 - 8\sin\Delta\theta)$	4
14	$P(8 - 8\cos\Delta\theta)$	4

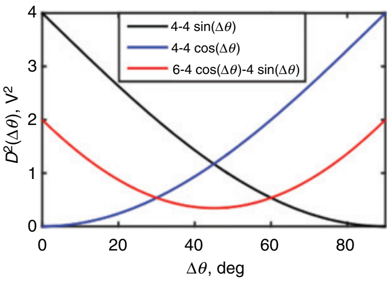

Fig. 1 *Minimum distance distribution in terms of Δθ for P = 1*

It is worth noting that the determinate solution is only related to the difference between θ_1 and θ_2 regardless of the specific angles. Thus, we can set $\theta_1 = 0°$ and $\theta_2 = 30°$ at the BS to simplify the design of our proposed NOMA without transmitting the CSI to the BS from the users or informing θ_k to the users from the BS. For decoding with ML decoder only needs the knowledge of h_k and θ_k given the synchronisation is achieved already, and the CSI is usually obtained at the receivers via channel estimation, then the decoding can be conducted readily with fixed θ_k which is known at the BS and receivers.

Experimental setup and simulation results: To evaluate the performance of our proposed approach, the capacity of the kth user for OMA (TDMA and FDMA) is provided for comparison, which is given by

$$C_k(W) = \log_2(N_k) - \frac{1}{N_k}\sum_{n_1=1}^{N_k} E\big[\log_2[\Gamma(W)]\big], \quad k = 1,\ 2 \qquad (7)$$

where $\Gamma(W) = \big((\sum_{n_2=1}^{N_k} \exp(-|h_k[\sqrt{P}s_k(n_1) - \sqrt{P}s_k(n_2)] + z|^2/WN_0))/(\exp(-(|z|^2/WN_0)))\big)$, N_k is the size of the constellation for user k. The sum capacity of two users for TDMA and FDMA is given by $C_{\text{TDMA}}(W) = \alpha C_1(W) + (1-\alpha)C_2(W)$ and $C_{\text{FDMA}}(W) = \alpha C_1(\alpha W) + (1-\alpha)C_2((1-\alpha)W)$, $0 < \alpha < 1$, respectively. We calculate the ergodic sum CCC of conventional NOMA and our proposed scheme with the SCCs constraint. Here, h_1 and h_2 are Rayleigh fading channels which are subject to $|\beta| \le \gamma$ assuming $\gamma = 6$ dB. The 16-point Gauss-Hermite quadrature is applied to approximate the expectations in (3), (4) and (7). We define $\text{SNR} = P/WN_0$ assuming $W = 1$ Hz. The power for each user in OMA is $2P$ which is the same as in the NOMA. The ergodic sum CCC values for NOMA and OMA with $\alpha = 0.5$ are shown in Fig. 2. All the simulation results are obtained by averaging over 500 channel realisations.

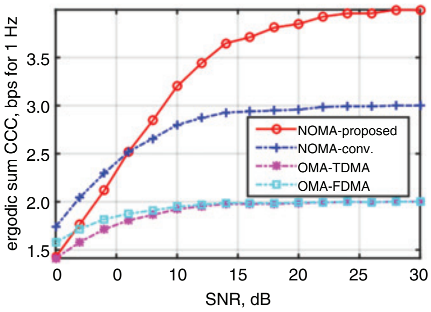

Fig. 2 *Ergodic sum CCC comparison for SCCs*

In Fig. 2, the ergodic sum CCC of both TDMA and FDMA asymptotically saturate to 2 bit/s, whereas conventional NOMA (NOMA-conv.) can obtain 3 bit/s because of many-to-one mapping as mentioned in the *algorithm design* section. However, for our proposed scheme, the ergodic sum CCC can achieve 4 bit/s and outperforms the conventional NOMA and OMA. It is worth noting that the sum CCC for FDMA has about 3 dB gain over TDMA at low SNR (before obtaining saturated) because only half bandwidth is occupied for each FDMA user and the equivalent noise in FDMA is also half of that in TDMA. Moreover, the sum CCC for conventional NOMA increases faster than our proposed method at low SNR because overlapping points exist, which lead to larger distance distribution among the superposed constellation.

Conclusion: We have proposed an NOMA scheme based on VCO to construct a uniquely decodable sum constellation. A setup of a fixed angle pair is derived to simplify the system implementation without the feedback of CSI at the transmitter. Computer simulations demonstrate that our proposed scheme can achieve a throughout of 4 bit/s/Hz which is twice of the sum CCC of OMA schemes in the scenario of SCCs with QPSK constellation inputs. Our proposed fixed-θ_k NOMA can be used for grouping cell-edge users and further improve the overall capacity of communications systems.

Acknowledgment: This work was supported by the China Scholarship Council (No. 201706245027).

Submitted: *16 November 2018* E-first: *26 February 2019*
doi: 10.1049/el.2018.7754
One or more of the Figures in this Letter are available in colour online.

Wenlong Xia, Qingdang Meng and Qingchuan Tao (*School of Electronics and Information Engineering, Sichuan University, Chengdu, People's Republic of China*)

✉ E-mail: xwenlong@scu.edu.cn

Ray T. Chen (*Electrical and Computer Engineering, The University of Texas at Austin, TX, USA*)

References

1 Saito, Y., Kishiyama, Y., Benjebbour, A., *et al.*: 'Non-orthogonal multiple access (NOMA) for cellular future radio access'. IEEE VTC Spring'13, Dresden, Germany, June 2013, pp. 1–5
2 Islam, S.M.R., Avazov, N., Dobre, O.A., *et al.*: 'Power-domain non-orthogonal multiple access (NOMA) in 5G systems: potentials and challenges', *IEEE Commun. Surv. Tutor. 2nd Quart.*, 2017, **19**, (2), pp. 721–742
3 Pan, H., Lu, L., and Liew, S.C.: 'Practical power-balanced non-orthogonal multiple access', *IEEE J. Sel. Areas Commun.*, 2017, **35**, (10), pp. 2312–2327
4 Ding, Z., Zhao, Z., Peng, M., *et al.*: 'On the spectral efficiency and security enhancements of NOMA assisted multicast-unicast streaming', *IEEE Trans. Commun.*, 2017, **65**, (7), pp. 3151–3163
5 Yang, G., Zhou, Y., and Xia, W.: 'Virtual channel optimization for overloaded MIMO systems', *IEEE Trans. Circuits Syst. II, Express Briefs*, 2018, **65**, (3), pp. 331–335
6 Harshan, J., and Rajan, B.: 'On two-user Gaussian multiple access channels with finite input constellations', *IEEE Trans. Inf. Theory*, 2011, **57**, (3), pp. 1299–1327
7 Goldsmith, A.: 'Wireless Communications' (Cambridge University Press, New York, NY, USA, 2005)