Note on the saturation of the norm inequalities between diamond and nuclear norm

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Abstract—The diamond norm plays an important role in quantum information and operator theory. Recently, it has also been proposed as a regularizer for low-rank matrix recovery. The norm constants that bound the diamond norm in terms of the nuclear norm (also known as trace norm) are explicitly known. This note provides a simple characterization of all operators saturating the upper and the lower bound.

I. INTRODUCTION

The diamond norm [1], [2] plays an important role in quantum information and in operator theory, where it equals – essentially¹ – the norm of complete boundedness or cb-norm. Recently, some of the present authors proposed its use as a regularizer for low-rank matrix recovery in the context of compressed sensing [5]. Given few random linear measurements on a low rank matrix, traditionally one reconstructs it by minimizing the nuclear norm subject to the constraints given by the measurements. Kliesch et al. [5] recently showed that replacing the nuclear norm by the diamond norm can be beneficial for the reconstruction. In particular, it was proven that for operators saturating the norm inequality from Theorem 1 below, diamond norm regularization performs at least as well as (and heuristically better than) the usual nuclear norm regularization [5]. The set of operators saturating this norm inequality was explicitly characterized [5] (see Theorem 1). This characterization has turned out to also

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¹ The diamond norm of a map is the cb-norm of its adjoint $||X||_{\diamond} = ||X^{\dagger}||_{cb}$ [3], [4].

follow from an analysis of typical distances between quantum channels [6].

These previous analyses are based on a semidefinite programming (SDP) formulation [3] for the diamond norm—henceforth called *Watrous' SDP*. The SDPformulation renders the proof quite technical.

In this note we present a simple and compact proof of this characterization. Moreover, we also characterize all matrices saturating a converse norm inequality.

A. Notation

The space of linear maps on \mathcal{V} is denoted by $L(\mathcal{V})$ and the identity by $\mathbb{1}_{\mathcal{V}} \in L(\mathcal{V})$. The *tensor products* of operators or vector spaces are both denoted by \otimes . A nonnegative real number σ is called a *singular value* of an operator $A \in L(\mathcal{V})$ if and only if, there exist normalized vectors $u, v \in \mathcal{V}$ such that $Av = \sigma u$. This implies $A^{\dagger}u = \sigma v$ for the *adjoint* operator A^{\dagger} . We call such vectors u, v left singular and right singular vector for σ , respectively. The operator square root of a positive semidefinite operator $A \succeq 0$ is defined to be the unique positive semidefinite operator \sqrt{A} obeying $\sqrt{A}^2 = A$. We will use the nuclear norm $\|\cdot\|_1$, Frobenius norm $\|\cdot\|_2$ and spectral norm $\|\cdot\|_{\infty}$ defined by

$$\|A\|_{1} \coloneqq \operatorname{Tr} \sqrt{A^{\dagger} A}, \qquad (1)$$

$$\|A\|_2 \coloneqq \sqrt{\operatorname{Tr}[A^{\dagger}A]}, \qquad (2)$$

$$||A||_{\infty} \coloneqq \sup_{x \in \mathcal{V}} \frac{||Ax||_2}{||x||_2}.$$
 (3)

Following [5], we define the square norm of a bipartite operator $X \in L(W \otimes V)$ to be

$$\|X\|_{\Box} = \sup_{\substack{A,B \in \mathcal{L}(\mathcal{V}) \\ \|A\|_2 = \|B\|_2 = \sqrt{\dim(\mathcal{V})}}} \left\| (\mathbb{1}_{\mathcal{W}} \otimes A) X (\mathbb{1}_{\mathcal{W}} \otimes B) \right\|_1$$
(4)

The square norm is closely related [5] to the diamond norm $\|\cdot\|_{\diamond}$ by $\|J(M)\|_{\Box} = \dim(\mathcal{V}) \|M\|_{\diamond}$, where $M : L(\mathcal{V}) \to L(\mathcal{W})$ is a linear map, J is the Choi-Jamiołkowski isomorphism [7], [8] (so that $J(M) \in$ $L(\mathcal{W} \otimes \mathcal{V})$). Finally, the partial trace $\operatorname{Tr}_{\mathcal{W}} : L(\mathcal{W} \otimes \mathcal{V}) \to$ $L(\mathcal{V})$ is the linear map defined on product operators $(A \otimes B) \in L(\mathcal{W} \otimes \mathcal{V})$ by $\operatorname{Tr}_{\mathcal{W}}[A \otimes B] = \operatorname{Tr}[A]B$ and linearly extended to all $L(\mathcal{W} \otimes \mathcal{V})$.

II. RESULT

The following equivalence of norms holds (see, e.g., [5]):

$$||X||_1 \le ||X||_{\square} \le \dim(\mathcal{V}) ||X||_1$$
. (5)

We provide a characterization of (i) all operators saturating the upper bound and (ii) the lower bound on $||X||_{\Box}$.

Theorem 1 (Saturation of the lower bound [5]). Let $X \in L(\mathcal{W} \otimes \mathcal{V})$. Then $||X||_1 = ||X||_{\Box}$ if and only if

$$\operatorname{Tr}_{\mathcal{W}}\left[\sqrt{XX^{\dagger}}\right] = \operatorname{Tr}_{\mathcal{W}}\left[\sqrt{X^{\dagger}X}\right] = \frac{\|X\|_{1}}{\dim(\mathcal{V})}\mathbb{1}_{\mathcal{V}}.$$
 (6)

This theorem was proven [5] using Watrous' SDP [3] and complementary slackness. It also follows from the proof of another new norm inequality [6, Remark 3], also based on Watrous' SDP.

Below we provide a shorter and more direct proof. The similar upper bound is saturated as follows.

Theorem 2 (Saturation of the upper bound).

Let $X \in L(\mathcal{W} \otimes \mathcal{V})$. Then $||X||_{\square} = \dim(\mathcal{V}) ||X||_1$ if and only if there exist rank-1 projectors $\phi \phi^{\dagger}, \psi \psi^{\dagger} \in L(\mathcal{V})$ such that

$$\operatorname{Tr}_{\mathcal{W}}\left[\sqrt{XX^{\dagger}}\right] = \|X\|_{1}\psi\psi^{\dagger} \quad and \tag{7}$$

$$\operatorname{Tr}_{\mathcal{W}}\left[\sqrt{X^{\dagger}X}\right] = \|X\|_{1} \phi \phi^{\dagger} .$$
(8)

III. PROOFS

In this section we first state our auxiliary statements and then the proofs of our theorems.

A. Auxiliary statements

The concept of sign functions of real numbers is extendable to non-Hermitian matrices.

Definition 3 (Sign matrix). For any matrix $X \in L(\mathcal{V})$ with singular value decomposition $X = U\Sigma V^{\dagger}$ we define its sign matrix to be $S_X \coloneqq VU^{\dagger}$.

Note that the sign matrix obeys

$$XS_X = U\Sigma U^{\dagger} = \sqrt{XX^{\dagger}}, \qquad (9)$$

$$S_X X = V \Sigma V^{\dagger} = \sqrt{X^{\dagger} X} \,. \tag{10}$$

The eigenvectors of XS_X and S_XX are *left singular* and right singular vectors of X, respectively. The saturation results from our theorems are derived using similar saturation results for Schatten norms. For any matrix $X \in L(\mathcal{V})$ with $n \coloneqq \dim(\mathcal{V})$ it holds that $\|X\|_1 \le \sqrt{n} \|X\|_2$ and we observe that this bound is saturated for unitary operators.

Observation 4 (Saturation: 1 and 2-norm).

Let $X \in L(\mathcal{V})$. Then $||X||_2 = \frac{1}{\sqrt{n}} ||X||_1$ if and only if $\frac{\sqrt{n}}{\|X\|_1}X$ is unitary.

Schatten norms satisfy Hölder's inequality, i.e., for $A, B \in L(\mathcal{V})$ it holds that $||AB||_1 \leq ||A||_{\infty} ||B||_1$. The saturation condition involves the range ran(B) of B.

Proposition 5 (Saturation of Hölder's inequality). Let $A, B \in L(\mathcal{V})$. Then the following are equivalent:

- i) Tightness in Hölder's inequality, i.e. $||AB||_1 =$ $||A||_{\infty} ||B||_{1}$
- ii) Every vector $x \in ran(B)$ is a right singular vector of A with singular value $||A||_{\infty}$ iii) The restriction of $\frac{A}{||A||_{\infty}}$ to ran(B) is an isometry.

A proof of this proposition is provided in the Appendix. Applying it twice yields a similar result for the iterated version of Hölder's inequality $||ABC||_1 \leq$ $||A||_{\infty} ||B||_{1} ||C||_{\infty}$ (for $A, B, C \in L(\mathcal{V})$).

Observation 6 (Saturation of iterated Hölder's inequality). Let be $A, B, C \in L(\mathcal{V})$.

- *Then* $||ABC||_1 = ||A||_{\infty} ||B||_1 ||C||_{\infty}$ *if and only if*
- i) Every vector $x \in ran(B)$ is a right singular vector of A with singular value $\|A\|_{\infty}$ and
- ii) Every vector $y \in \operatorname{ran}(B^{\dagger})$ is a left singular vector of C with singular value $||C||_{\infty}$.

Directly from the definition of the partial trace, it follows that

$$\operatorname{Tr}[X(\mathbb{1}_{\mathcal{W}} \otimes B)] = \operatorname{Tr}\left|\operatorname{Tr}_{\mathcal{W}}(X)B\right|$$
(11)

for all $X \in L(\mathcal{W} \otimes \mathcal{V})$ and $B \in L(\mathcal{V})$.

B. Proofs

Now we use the previous observations to prove our theorems.

Proof of Theorem 1. We recall the definition of the square norm,

$$\|X\|_{\Box} = \sup_{\substack{A,B \in \mathcal{L}(\mathcal{V}) \\ \|A\|_2 = \|B\|_2 = \sqrt{\dim(\mathcal{V})}}} \|(\mathbb{1}_{\mathcal{W}} \otimes A) X (\mathbb{1}_{\mathcal{W}} \otimes B)\|_1$$
(12)

For convenience we define $\tilde{X}_A \coloneqq (\mathbb{1}_W \otimes A) X$ and $n \coloneqq$ $\dim(\mathcal{V})$. Using the unitary invariance of the nuclear norm, the fact that $Tr[Y] \leq ||Y||_1$, and Eq. (11) we obtain

$$\|(\mathbb{1}_{\mathcal{W}} \otimes A) X (\mathbb{1}_{\mathcal{W}} \otimes B)\|_{1}$$

$$\geq \operatorname{Tr} \left[S_{\tilde{X}_{A}} \tilde{X}_{A} (\mathbb{1}_{\mathcal{W}} \otimes B) \right]$$

$$= \operatorname{Tr} \left[\sqrt{\tilde{X}_{A}^{\dagger} \tilde{X}_{A}} (\mathbb{1}_{\mathcal{W}} \otimes B) \right]$$

$$= \operatorname{Tr} \left[\operatorname{Tr}_{\mathcal{W}} \left[\sqrt{\tilde{X}_{A}^{\dagger} \tilde{X}_{A}} \right] B \right].$$
(13)

Choosing $B \propto \text{Tr}_{W} \sqrt{\tilde{X}_A^{\dagger} \tilde{X}_A}$ (with proportionality constant chosen such that $||B||_2 = \sqrt{n}$), which will turn out to yield the optimal value, we obtain

$$\|X\|_{\Box} \ge \sup_{A \in \mathcal{L}(\mathcal{V})} \left\{ \sqrt{n} \left\| \operatorname{Tr}_{\mathcal{W}} \sqrt{\tilde{X}_{A}^{\dagger} \tilde{X}_{A}} \right\|_{2}, \, \|A\|_{2} = \sqrt{n} \right\}$$
(14)

Using that $\sqrt{n} \|Y\|_2 \ge \|Y\|_1$ for all $Y \in L(\mathcal{V})$ yields

$$\sqrt{n} \left\| \operatorname{Tr}_{\mathcal{W}} \sqrt{\tilde{X}_{A}^{\dagger} \tilde{X}_{A}} \right\|_{2} \geq \left\| \operatorname{Tr}_{\mathcal{W}} \sqrt{\tilde{X}_{A}^{\dagger} \tilde{X}_{A}} \right\|_{1} \qquad (15)$$
$$= \left\| (\mathbb{1}_{\mathcal{W}} \otimes A) X \right\|_{1}.$$

Analogously as before, we proceed by using the unitary invariance of the 1-norm and the sign matrix S_X from the right to obtain

$$\sqrt{n} \left\| \operatorname{Tr}_{\mathcal{W}} \sqrt{\tilde{X}_{A}^{\dagger} \tilde{X}_{A}} \right\|_{2} \ge \left\| \left(\mathbb{1}_{\mathcal{W}} \otimes A \right) \sqrt{X X^{\dagger}} \right\|_{1}.$$
 (16)

We choose $A \propto \text{Tr}_{W} \sqrt{XX^{\dagger}}$ and combine it with the bound (14) to finally arrive at

$$\|X\|_{\Box} \ge \sqrt{n} \left\| \operatorname{Tr}_{\mathcal{W}} \sqrt{XX^{\dagger}} \right\|_{2} \ge \left\| \operatorname{Tr}_{\mathcal{W}} \sqrt{XX^{\dagger}} \right\|_{1} (17)$$
$$= \|X\|_{1}.$$

The equality of both norms holds if and only if all inequalities are saturated. In particular we have that

$$\sqrt{n} \left\| \operatorname{Tr}_{\mathcal{W}} \sqrt{XX^{\dagger}} \right\|_{2} = \left\| \operatorname{Tr}_{\mathcal{W}} \sqrt{XX^{\dagger}} \right\|_{1}$$
(18)

in the bound (17) if and only if $\operatorname{Tr}_{\mathcal{W}}\sqrt{XX^{\dagger}}$ is unitary up to a normalization factor (Observation 4). Since $\operatorname{Tr}_{\mathcal{W}}\sqrt{XX^{\dagger}}$ is also positive semidefinite we obtain $\operatorname{Tr}_{\mathcal{W}}\sqrt{XX^{\dagger}} = \frac{\|X\|_1}{n}\mathbb{1}$ as the only possible operator. From the bound (15) follows, with the same argument, that $\operatorname{Tr}_{\mathcal{W}}\sqrt{X}_A^{\dagger}\tilde{X}_A \propto \mathbb{1}$. This relation implies the second desired identity $\operatorname{Tr}_{\mathcal{W}}\sqrt{X^{\dagger}X} = \frac{\|X\|_1}{n}\mathbb{1}$.

Proof of Theorem 2. " \Rightarrow ": We use the hypothesis and split the 1-norm of products with an iterated Hölder's inequality in order to maximize separately over *A* and *B* in the definition of the square norm (4),

$$n \|X\|_{1} = \|X\|_{\Box}$$

$$\leq \sup_{\substack{A,B \in \mathcal{L}(\mathcal{V}) \\ \|A\|_{2} = \|B\|_{2} = \sqrt{n} \\}} \|\mathbb{1}_{\mathcal{W}} \otimes A\|_{\infty} \|X\|_{1} \|\mathbb{1}_{\mathcal{W}} \otimes B\|_{\infty}$$

$$= n \|X\|_{1} .$$
(19)

The largest possible value is attained with rank 1 matrices $A = \sqrt{n\nu}\psi^{\dagger}$, $B = \sqrt{n}\phi\mu^{\dagger}$ for normalized $\nu, \mu, \phi, \psi \in \mathcal{V}$. Since the inequality is saturated we conclude with Observation 6 that $X = Y \otimes \psi\phi^{\dagger}$ for an arbitrary non-zero operator $Y \in L(\mathcal{W})$, and the result follows.

" \leftarrow ": From the hypothesis we have that $X = Y \otimes \psi \phi^{\dagger}$. Instead of maximizing in the definition of the square

norm (4) we just choose $A \propto \psi \psi^{\dagger}$, $B \propto \phi \phi^{\dagger}$. This choice yields

$$n \|X\|_{1} \geq \|X\|_{\Box}$$

$$\geq n \|(\mathbb{1}_{\mathcal{W}} \otimes \psi\psi^{\dagger}) (Y \otimes \psi\phi^{\dagger}) (\mathbb{1}_{\mathcal{W}} \otimes \phi\phi^{\dagger})\|_{1}$$

$$= n \|X\|_{1}$$
(20)

and the result follows.

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APPENDIX

In this appendix we provide the proof of the saturation condition for Hölder's inequality.

Proof of Proposition 5.

"ii) \Rightarrow iii)": $\frac{A}{\|A\|_{\infty}}$ maps an arbitrary $\phi \in \operatorname{ran}(B)$ from one singular basis to another. Hence, restricted to $\operatorname{ran}(B)$ it is an isometry.

"iii) \Rightarrow i)": We represent the isometry $\frac{A}{\|A\|_{\infty}}$ with a unitary matrix U that fulfills $\|A\|_{\infty} UB = AB$. Using the unitary invariance of the nuclear norm, we obtain $\|AB\|_1 = \|A\|_{\infty} \|UB\|_1 = \|A\|_{\infty} \|B\|_1$.

"i) \Rightarrow ii)": We denote the *i*-th largest singular value of a matrix X with $\sigma_i(X)$. We upper bound the nuclear norm by splitting the singular values of the matrix as [9, Problem 3.3.4]

$$||AB||_1 = \sum_{i=1}^n \sigma_i(AB) \le \sum_{i=1}^n \sigma_i(A)\sigma_i(B).$$
 (21)

Upper bounding the singular values of A by the largest singular value yields

$$\sum_{i=1}^{n} \sigma_i(A) \sigma_i(B) \le \sum_{i=1}^{\operatorname{rank}(B)} \|A\|_{\infty} \sigma_i(B)$$

= $\|A\|_{\infty} \|B\|_1$. (22)

By assumption, every inequality is saturated. In particular, the largest rank(B) singular values of A are all equal. Furthermore, $\sigma_i(AB) = ||A||_{\infty} \sigma_i(B)$ and, thus, all vectors $x \in \operatorname{ran}(B)$ are right singular vectors of A with singular value $||A||_{\infty}$.