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We consider a paving property for a maximal abelian $*$ -subalgebra (MASA) A in a von Neumann algebra M , that we call *so-paving*, involving approximation in the *so*-topology, rather than in norm (as in classical Kadison–Singer paving). If A is the range of a normal conditional expectation, then *so-paving* is equivalent to norm paving in the ultrapower inclusion $A^\omega \subset M^\omega$. We conjecture that any MASA in any von Neumann algebra satisfies *so-paving*. We use work of Marcus, Spielman and Srivastava to check this for all MASAs in $\mathcal{B}(\ell^2\mathbb{N})$, all Cartan subalgebras in amenable von Neumann algebras and in group measure space II_1 factors arising from profinite actions. By earlier work of Popa, the conjecture also holds true for singular MASAs in II_1 factors, and we obtain here an improved paving size $C\varepsilon^{-2}$, which we show to be sharp.

1. Introduction

A famous problem of R. V. Kadison and I. M. Singer [1959] asked whether the diagonal MASA (maximal abelian $*$ -subalgebra) \mathcal{D} in the algebra $\mathcal{B}(\ell^2\mathbb{N})$ of all linear bounded operators on the Hilbert space $\ell^2\mathbb{N}$ satisfies the *paving property*, requiring that, for any $x \in \mathcal{B}(\ell^2\mathbb{N})$ with 0 on the diagonal and any $\varepsilon > 0$, there exists a partition of 1 with projections $p_1, \dots, p_n \in \mathcal{D}$ such that $\|\sum_i p_i x p_i\| \leq \varepsilon \|x\|$.

In striking work, A. Marcus, D. Spielman and N. Srivastava [Marcus et al. 2015] have settled this question in the affirmative, while also obtaining an estimate for the minimal number of projections necessary for such ε paving, $n(x, \varepsilon) \leq 12^4 \varepsilon^{-4}$ for all $x = x^* \in \mathcal{B}(\ell^2\mathbb{N})$.

On the other hand, in [Popa 2014] the paving property for $\mathcal{D} \subset \mathcal{B}(\ell^2\mathbb{N})$ has been shown to be equivalent to the paving property for the ultrapower inclusion $D^\omega \subset R^\omega$, where R is the hyperfinite II_1 factor, D is its Cartan subalgebra and ω is a free ultrafilter on \mathbb{N} . (Recall from [Dixmier 1954; Feldman and Moore 1977] that a subalgebra A in a von Neumann algebra M is a *Cartan subalgebra* if it is a MASA, there exists a normal conditional expectation of M onto A , and the normalizer of A in M , $\mathcal{N}_M(A) = \{u \in \mathcal{U}(M) \mid uAu^* = A\}$, generates M .) It was also shown in [Popa 2014] that if A is a singular MASA in R , or, more generally, in an arbitrary II_1 factor M , then $A^\omega \subset M^\omega$ has the paving property, with corresponding paving size majorized by $C\varepsilon^{-3}$. (Recall from [Dixmier 1954] that a MASA $A \subset M$ is *singular* in M if its normalizer is trivial, that is, $\mathcal{N}_M(A) \subset A$.)

Inspired by these results, we consider in this paper a new, weaker paving property for an arbitrary MASA A in a von Neumann algebra M that we call *so-paving*, which requires that, for any

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$x \in M_{\text{sa}} = \{x \in M \mid x = x^*\}$ and $\varepsilon > 0$, there exists n such that x can be (ε, n) *so-paved*, that is, for any *so*-neighborhood \mathcal{V} of 0 there exists a partition of 1 with projections p_1, \dots, p_n in A and an element $a \in A$ satisfying $\|a\| \leq \|x\|$ and $\|q(\sum_i p_i x p_i - a)q\| \leq \varepsilon \|x\|$ for some projection $q \in M$ with $1 - q \in \mathcal{V}$ (see Section 2). We prove that, if there exists a normal conditional expectation from M onto A , then *so*-paving is equivalent to the property that, for any $x \in M_{\text{sa}}$ and $\varepsilon > 0$, there exists n such that x can be approximated in the *so*-topology with elements that can be (ε, n) norm paved (see Theorem 2.7). If in addition A is countably decomposable, then *so*-paving with uniform bound on the number n necessary to (ε, n) *so*-pave any $x \in M_{\text{sa}}$ is equivalent to the ultrapower inclusion $A^\omega \subset M^\omega$ satisfying norm paving (with M^ω as defined in [Ocneanu 1985]). In particular, this shows that *so*-paving amounts to norm paving in the case $\mathcal{D} \subset \mathcal{B}(\ell^2\mathbb{N})$.

We conjecture that any MASA in any von Neumann algebra satisfies the *so*-paving property (see Conjecture 2.8). We use [Marcus et al. 2015] to check this conjecture for all MASAs in $\mathcal{B}(\ell^2\mathbb{N})$ (i.e., for the remaining case of the diffuse MASA $L^\infty([0, 1]) \subset \mathcal{B}(L^2([0, 1]))$; see Section 3), for all Cartan subalgebras in amenable von Neumann algebras, as well as for any Cartan subalgebra in a group measure space II_1 factor arising from a free ergodic measure-preserving profinite action (see Section 4). At the same time, we prove that, for a von Neumann algebra M with separable predual, norm paving over a MASA $A \subset M$ occurs if and only if M is of type I and there exists a normal conditional expectation of M onto A (see Theorem 3.3).

For singular MASAs $A \subset M$, where the conjecture already follows from results in [Popa 2014], we improve upon the paving size obtained there, by showing that any finite number of elements in M^ω can be simultaneously ε paved over A^ω with $n < 1 + 16\varepsilon^{-2}$ projections (see Theorem 5.1). Moreover, this estimate is sharp: given any MASA in a finite factor, $A \subset M$, and any $\varepsilon > 0$, there exists $x \in M_{\text{sa}}$ with zero expectation onto A such that, if $\|\sum_{i=1}^n p_i x p_i\| \leq \varepsilon \|x\|$ for some partition of 1 with projections in A , then n must be at least ε^{-2} (see Proposition 5.4). We include a discussion on the multipaving size for $\mathcal{D} \subset \mathcal{B}(\ell^2\mathbb{N})$ and, more generally, for Cartan subalgebras (see Remark 5.2).

2. A paving conjecture for MASAs

We will consider several paving properties for a MASA A in a von Neumann algebra M . For convenience we first recall the initial Kadison–Singer paving property [1959], for which we use the following terminology.

Definition 2.1. We say an element $x \in M$ is (ε, n) *pavable over* A if there exist projections $p_1, \dots, p_n \in A$ and $a \in A$ such that $\|a\| \leq \|x\|$, $\sum_{i=1}^n p_i = 1$ and $\|\sum_{i=1}^n p_i x p_i - a\| \leq \varepsilon \|x\|$. We denote by $\mathfrak{n}(A \subset M; x, \varepsilon)$ (or just $\mathfrak{n}(x, \varepsilon)$, if no confusion is possible), the smallest such n . Also, we say that x is *pavable* (over A) if, for every $\varepsilon > 0$, there exists an n such that x is (ε, n) pavable. We say that $A \subset M$ has the *paving property* if any $x \in M$ is pavable. We will sometimes use the terminology *norm pavable/paving* instead of just pavable/paving, when we need to underline the difference with other paving properties.

It is not really crucial to impose $\|a\| \leq \|x\|$. Indeed, without that assumption, the element $a \in A$ in an (ε, n) norm paving of x satisfies $\|a\| \leq (1 + \varepsilon)\|x\|$, so that, replacing a by $a' = (1 + \varepsilon)^{-1}a$, we have $\|a'\| \leq \|x\|$ and $\|\sum_i p_i x p_i - a'\| \leq 2\varepsilon \|x\|$.

Also note that, if there exists a normal conditional expectation E of M onto A , then the element $a \in A$ in an (ε, n) norm paving of x satisfies $\|E(x) - a\| \leq \varepsilon\|x\|$, so that $\|\sum_i p_i x p_i - E(x)\| \leq 2\varepsilon\|x\|$. In the presence of a normal conditional expectation, one often defines (ε, n) norm pavability by requiring the partition $p_1, \dots, p_n \in A$ to satisfy $\|\sum_i p_i x p_i - E(x)\| \leq \varepsilon\|x\|$.

Finally note that, if $y_1, y_2 \in M_{sa}$ are (ε, n) pivable, then $y_1 + iy_2$ is $(2\varepsilon, n^2)$ pivable. Thus, in order to obtain the paving property for $A \subset M$, it is sufficient to check pavability of self-adjoint elements in M .

We next define two weaker notions of paving, involving approximation in the *so*-topology rather than in norm.

Definition 2.2. An element $x \in M$ is (ε, n) *so-pavable over* A if, for every strong neighborhood \mathcal{V} of 0 in M , there exist projections $p_1, \dots, p_n \in A$, an element $a \in A$ and a projection $q \in M$ such that $\|a\| \leq \|x\|$, $\sum_{i=1}^n p_i = 1$, $\|q(\sum_i p_i x p_i - a)q\| \leq \varepsilon\|x\|$ and $1 - q \in \mathcal{V}$. We denote by $n_s(x, \varepsilon)$ the smallest such n . An element $x \in M$ is *so-pavable over* A if, for any $\varepsilon > 0$, there exists n such that x is (ε, n) *so-pavable*. We say that $A \subset M$ has the *so-paving* property if any $x \in M_{sa}$ is *so-pavable*.

It is easy to see that, if M is a finite von Neumann algebra with a faithful normal trace τ and $x \in M_{sa}$, then x is (ε, n) *so-pavable* if and only if, given any $\delta > 0$, there exist a partition of 1 with projections $p_1, \dots, p_n \in A$ and $a \in A_{sa}$, $\|a\| \leq \|x\|$, such that the spectral projection q of $\sum_i p_i x p_i - a$ corresponding to $[-\varepsilon\|x\|, \varepsilon\|x\|]$ satisfies $\tau(1 - q) \leq \delta$. As pointed out in [Popa 2014, Remark 2.4.1°], if ω is a free ultrafilter on \mathbb{N} , then $x \in M_{sa}$ has this latter property if and only if, when viewed as an element in M^ω , it is pivable over the ultrapower MASA A^ω of M^ω .

Definition 2.3. An element $x \in M$ is $(\varepsilon, n; \kappa)$ *app-pavable over* A if it can be approximated in the *so*-topology by a net of (ε, n) pivable elements in M bounded in norm by $\kappa\|x\|$. An element $x \in M$ is *app-pavable over* A if there exists κ_0 such that, for any $\varepsilon > 0$, there exists n such that x is $(\varepsilon, n; \kappa_0)$ *app-pavable*. We say that $A \subset M$ has the *app-paving* property if any $x \in M_{sa}$ is *app-pavable*.

Obviously, norm paving implies *so*- and *app*-paving, with $n(x, \varepsilon) \geq n_s(x, \varepsilon)$ for all x . The next result shows that, if a MASA is the range of a normal conditional expectation, then *so*- and *app*-pavability are in fact equivalent.

Proposition 2.4. Let M be a von Neumann algebra and $A \subset M$ a MASA with the property that there exists a normal conditional expectation $E : M \rightarrow A$. Let $x \in M_{sa}$, $n \in \mathbb{N}$, $\varepsilon > 0$.

- (1) If x is $(\varepsilon, n; \kappa)$ *app-pavable* for some $\kappa \geq 1$, then x is $(2\kappa\varepsilon', n)$ *so-pavable* for any $\varepsilon' > \varepsilon$.
- (2) If x is (ε, n) *so-pavable*, then x is $(\varepsilon', n; 3)$ *app-pavable* for any $\varepsilon' > \varepsilon$.

Proof. (1) Let $x_j \in M_{sa}$ with $\|x_j\| \leq \kappa\|x\|$ for all j be such that x_j is (ε, n) pivable for all j and x_j converges to x in the *so*-topology. Fix $\varepsilon' > \varepsilon$. We prove that x is $(2\kappa\varepsilon', n)$ *so-pavable*, i.e., that, given any *so*-neighborhood \mathcal{V} of 0, there exist a partition of 1 with projections $p_1, \dots, p_n \in A$, an element $a \in A$ and $q \in \mathcal{P}(M)$ such that $1 - q \in \mathcal{V}$ and $\|q(\sum_i p_i x p_i - a)q\| \leq 2\kappa\varepsilon'\|x\|$.

Note that, if necessary by changing the multiplicity of the representation of M on the Hilbert space \mathcal{H} , we may assume that the given neighborhood \mathcal{V} is of the form $\mathcal{V} = \{x \in M_{sa} \mid \|x\xi\| \leq \alpha\}$ for some unit vector $\xi \in \mathcal{H}$ and $\alpha > 0$.

For every j , choose a partition of 1 by projections $p_{j,1}, \dots, p_{j,n} \in A$ and an element $a_j \in A$ such that

$$\left\| \sum_{i=1}^n p_{j,i} x_j p_{j,i} - a_j \right\| \leq \varepsilon \|x_j\| \leq \kappa \varepsilon \|x\|.$$

Applying the conditional expectation E , it also follows that $\|E(x_j) - a_j\| \leq \kappa \varepsilon \|x\|$. Therefore,

$$\left\| \sum_{i=1}^n p_{j,i} (x_j - E(x_j)) p_{j,i} \right\| \leq 2\kappa \varepsilon \|x\|.$$

Define the self-adjoint elements

$$T_j = \sum_{i=1}^n p_{j,i} (x - E(x)) p_{j,i} \quad \text{and} \quad S_j = \sum_{i=1}^n p_{j,i} (x_j - E(x_j)) p_{j,i}.$$

Let $\delta = 2(\varepsilon' - \varepsilon)\kappa \|x\|$. Recall that the normal conditional expectation E is automatically faithful because its support is a projection in $A' \cap M = A$ and thus equal to 1. So, we can apply Lemma 2.5 and, since $x_j \rightarrow x$ strongly, we get that $T_j - S_j \rightarrow 0$ strongly. Thus, there exists j large enough such that $\|(T_j - S_j)\xi\| < \alpha\delta$.

We claim that, if we denote by q the spectral projection of $|T_j - S_j|$ corresponding to the interval $[0, \delta]$, then $\|(1-q)\xi\| < \alpha$, and so $1-q \in \mathcal{V}$. Indeed, if not, then $\|(1-q)\xi\| \geq \alpha$ and thus $\||T_j - S_j|(1-q)\xi\| \geq \alpha\delta$, implying that

$$\|(T_j - S_j)\xi\| \geq \||T_j - S_j|(1-q)\xi\| \geq \alpha\delta > \|(T_j - S_j)\xi\|,$$

a contradiction.

On the other hand, $a = E(x)$ satisfies $\|a\| \leq \|x\|$ and we also have the estimates

$$\left\| q \left(\sum_{i=1}^n p_{j,i} (x - E(x)) p_{j,i} \right) q \right\| = \|qT_jq\| \leq \|q(T_j - S_j)q\| + \|qS_jq\| \leq \delta + 2\kappa\varepsilon\|x\| = 2\kappa\varepsilon'\|x\|.$$

This finishes the proof of (1).

(2) Note that if $\varepsilon' \geq 2$ then there is nothing to prove. So, without any loss of generality, we may assume $0 < \varepsilon < \varepsilon' < 2$. Let $\alpha = 1 - (\varepsilon' - \varepsilon)/2$ and $\gamma = 1 - (\alpha\varepsilon' - \varepsilon)/6$. Note that $\varepsilon' < 2$ implies $\alpha\varepsilon' > \varepsilon$, so $\gamma < 1$. We clearly also have $\gamma > \alpha$.

Let $x \in M_{sa}$ be (ε, n) *so*-pavable. Fix an open *so*-neighborhood \mathcal{W} of 0 in M . We construct an (ε', n) pavable element $y \in M_{sa}$ with $\|y\| \leq 3\|x\|$ and $x - y \in \mathcal{W}$. We may assume that $x \neq 0$.

By the lower semicontinuity of the norm with respect to the *so*-topology, it follows that the set

$$\mathcal{W}_1 = \mathcal{W} \cap \{h \in M \mid \|x - h\| > \gamma\|x\|\}$$

is an open *so*-neighborhood of 0 in M . Choose an open *so*-neighborhood \mathcal{W}_0 of 0 such that $\mathcal{W}_0 + \mathcal{W}_0 \subset \mathcal{W}_1$.

Using Lemma 2.5 below to realize the second point, we can fix an *so*-neighborhood \mathcal{V}_1 of 0 such that, for every projection $q \in M$ with $1 - q \in \mathcal{V}_1$, we have that:

- $x - q x q \in \mathcal{W}_0$;
- $q a q - a \in \mathcal{W}_0$ for all $a \in A$ with $\|a\| \leq \|x\|$.

Again using Lemma 2.5 below, we can fix an so -neighborhood $\mathcal{V}_0 \subset \mathcal{V}_1$ of 0 such that, for every projection $q \in M$ with $1 - q \in \mathcal{V}_0$, we have the following property:

- For any partition of 1 with projections $p_1, \dots, p_n \in A$, the spectral projection q' of $\sum_i p_i q p_i$ corresponding to the interval $(1 - ((\alpha\varepsilon' - \varepsilon)/(6n^2))^2, 1]$ satisfies $1 - q' \in \mathcal{V}_1$.

Since x is (ε, n) so -pavable, we can choose projections $p_1, \dots, p_n \in A$, an element $a \in A$ and a projection $q \in M$ such that $\|a\| \leq \|x\|$, $\sum_{i=1}^n p_i = 1$, $\|q(\sum_i p_i x p_i - a)q\| \leq \varepsilon\|x\|$ and $1 - q \in \mathcal{V}_0$.

Let e_i be the spectral projection of $p_i q p_i$ corresponding to the interval $(1 - ((\alpha\varepsilon' - \varepsilon)/(6n^2))^2, 1]$ for each i , and let $q' = \sum_i e_i$. By the last of the above properties, we have $1 - q' \in \mathcal{V}_1$. Define $y = q'(x - a)q' + a$ and note that $\|y\| \leq \|x - a\| + \|a\| \leq 3\|x\|$. We will prove that $x - y \in \mathcal{W}$ and that y is (ε', n) pavable.

Indeed, because $1 - q' \in \mathcal{V}_1$, we have

$$x - y = (x - q' x q') + (q' a q' - a) \in \mathcal{W}_0 + \mathcal{W}_0 \subset \mathcal{W}_1.$$

So, $x - y \in \mathcal{W}$ and $\|y\| \geq \gamma\|x\|$. Since this implies $\|\gamma a\| \leq \|y\|$, in order to prove that y is (ε', n) pavable it is sufficient to prove that $\|\sum_i p_i y p_i - \gamma a\| \leq \varepsilon'\|y\|$. To see this, note first that we have

$$\sum_i p_i y p_i - \gamma a = \sum_i p_i q'(x - a)q' p_i + (1 - \gamma)a = \sum_i e_i(x - a)e_i + (1 - \gamma)a,$$

and thus

$$\left\| \sum_i p_i y p_i - \gamma a \right\| \leq \left\| \sum_i e_i(x - a)e_i \right\| + (1 - \gamma)\|x\|.$$

Since, by the definition of e_i , we have

$$\|e_i - e_i q\|^2 = \|e_i - e_i q e_i\| = \|e_i - e_i(p_i q p_i)\| \leq \left(\frac{\alpha\varepsilon' - \varepsilon}{6n^2} \right)^2,$$

it follows that $\|q' - q' q\| \leq \sum_i \|e_i - e_i q\| \leq n(\alpha\varepsilon' - \varepsilon)/(6n^2) = (\alpha\varepsilon' - \varepsilon)/(6n)$. Thus, since $e_i = q' p_i$, we get that

$$\|e_i - q' q p_i\| = \|(q' - q' q)p_i\| \leq \|q' q - q'\| \leq \frac{\alpha\varepsilon' - \varepsilon}{6n},$$

implying that

$$\begin{aligned} & \left\| \sum_i p_i y p_i - \gamma a \right\| \\ & \leq \left\| \sum_i e_i(x - a)e_i \right\| + (1 - \gamma)\|x\| \\ & \leq \sum_i \|e_i - q' q p_i\| \|x - a\| + \|q' q\| \left(\sum_i p_i x p_i - a \right) q q' + \sum_i \|x - a\| \|e_i - p_i q q'\| + (1 - \gamma)\|x\| \end{aligned}$$

$$\begin{aligned} &\leq \frac{\alpha\varepsilon' - \varepsilon}{3} \|x - a\| + \varepsilon\|x\| + (1 - \gamma)\|x\| \leq \frac{5\alpha\varepsilon' + \varepsilon}{6} \|x\| \\ &\leq \frac{5\alpha\varepsilon' + \varepsilon}{6} \gamma^{-1} \|y\| \leq \alpha\gamma^{-1} \varepsilon' \|y\| < \varepsilon' \|y\| \end{aligned}$$

where the two last inequalities hold true because $\varepsilon < \alpha\varepsilon'$ and $\alpha\gamma^{-1} < 1$. □

In the proof of the above Proposition 2.4, we used the following elementary lemma:

Lemma 2.5. *Let $M \subset \mathcal{B}(H)$ be a von Neumann algebra and $P \subset M$ a von Neumann subalgebra. Assume that P is finite and that $E : M \rightarrow P$ is a normal faithful conditional expectation. If (x_k) is a bounded net in M that strongly converges to 0, then the nets $(x_k a)$ converge strongly to 0 uniformly over all $a \in (P)_1$:*

$$\lim_k \left(\sup_{a \in (P)_1} \|x_k a \xi\| \right) = 0 \quad \text{for every } \xi \in H.$$

Proof. Since P is finite, we can fix a normal semifinite faithful (nsf) trace Tr on P with the property that the restriction of Tr to the center $\mathcal{Z}(P)$ is still semifinite. Define the nsf weight $\varphi = \text{Tr} \circ E$ on M and the corresponding space $\mathcal{N}_\varphi = \{x \in M \mid \varphi(x^*x) < \infty\}$. We complete \mathcal{N}_φ into a Hilbert space H_φ : to every $x \in \mathcal{N}_\varphi$ corresponds a vector $\hat{x} \in H_\varphi$, and M is faithfully represented on H_φ by $\pi_\varphi(x)\hat{y} = \widehat{xy}$.

Whenever $z \in \mathcal{Z}(P)$ is a projection with $\text{Tr}(z) < \infty$, we consider the normal positive functional $\varphi_z \in M_*$ given by $\varphi_z(x) = \varphi(zxz)$. Since these φ_z form a faithful family of normal positive functionals on M , it suffices to prove that

$$\lim_k \left(\sup_{a \in (P)_1} \varphi_z(a^* x_k^* x_k a) \right) = 0 \quad \text{for all projections } z \in \mathcal{Z}(P) \text{ with } \text{Tr}(z) < \infty. \tag{2-1}$$

We denote by J_φ the modular conjugation on H_φ . Since P belongs to the centralizer of the weight φ , we have that $\widehat{xa} = J_\varphi \pi_\varphi(a)^* J_\varphi \hat{x}$ for all $x \in \mathcal{N}_\varphi$ and $a \in P$. For $z \in \mathcal{Z}(P)$ with $\text{Tr}(z) < \infty$ and $a \in P$, we then find that

$$\varphi_z(a^* x_k^* x_k a) = \|\widehat{x_k a z}\|^2 = \|J_\varphi \pi_\varphi(a)^* J_\varphi \widehat{x_k z}\|^2 \leq \|a\|^2 \varphi_z(x_k^* x_k).$$

Since $\lim_k \varphi_z(x_k^* x_k) = 0$, we get (2-1) and the lemma is proved. □

Remark 2.6. For Lemma 2.5 to hold, both the finiteness of P and the existence of the normal faithful conditional expectation $E : M \rightarrow P$ are crucial. First note that the lemma fails for the diffuse MASA in $\mathcal{B}(H)$. It suffices to take $M = \mathcal{B}(L^2(\mathbb{T}))$ and $P = L^\infty(\mathbb{T})$, with respect to the normalized Lebesgue measure on \mathbb{T} . Consider the unitary operators $a_n \in P$ given by $a_n(z) = z^n$. We can also consider the $(a_n)_{n \in \mathbb{Z}}$ as an orthonormal basis of $L^2(\mathbb{T})$ and define x_k as the orthogonal projection onto the closure of $\text{span}\{a_n \mid n \geq k\}$. Then, $x_k \rightarrow 0$ strongly. With $\xi(z) = 1$ for all $z \in \mathbb{T}$, we find that $\sup_n \|x_k a_n \xi\|_2 = 1$ for every k . So, the existence of the conditional expectation E is essential.

The previous paragraph implies in particular that the lemma fails if $M = P = \mathcal{B}(H)$. So, also, the finiteness of P is essential.

We will now relate *so-* and *app-*pavability properties for a MASA $A \subset M$ having a normal conditional expectation $E_A : M \rightarrow A$, with the norm-pavability for the associated inclusion of ultrapower

algebras $A^\omega \subset M^\omega$. We will only consider the case when A is countably decomposable, i.e., when there exists a normal faithful state φ on A . We still denote by φ its extension to M given by $\varphi \circ E_A$.

For the reader's convenience, we recall Ocneanu's [1985] definition of the ultrapower of a von Neumann algebra. Given a free ultrafilter ω on \mathbb{N} , one lets I_ω be the C^* -algebra of all bounded sequences $(x_n)_n \in \ell^\infty(\mathbb{N}, M)$ that are s^* -convergent to 0 along the ultrafilter ω . One denotes by $M^{0,\omega}$ the multiplier (also called the binormalizer) of I_ω in $\ell^\infty(\mathbb{N}, M)$ (which is easily seen to be a C^* -algebra) and one defines M^ω to be the quotient $M^{0,\omega}/I_\omega$. This is shown in [Ocneanu 1985] to be a von Neumann algebra, called the ω -ultrapower of M . Since the constant sequences are in the multiplier $M^{0,\omega}$, we have a natural embedding $M \subset M^\omega$. It is easy to see that, if M is an atomic von Neumann algebra, then $M^\omega = M$; in particular, $\mathfrak{B}(\ell^2\mathbb{N})^\omega = \mathfrak{B}(\ell^2\mathbb{N})$.

To define the ultrapower MASA $A^\omega \subset M^\omega$, one proceeds as in [Popa 1995, Section 1.3]. One lets $E_A^{0,\omega} : \ell^\infty(\mathbb{N}, M) \rightarrow \ell^\infty(\mathbb{N}, A)$ be the conditional expectation defined by $E_A^{0,\omega}((x_n)_n) = (E_A(x_n))_n$. One notices that $E_A^{0,\omega}(I_\omega) = I_\omega \cap \ell^\infty(\mathbb{N}, A) = \{(a_n) \in \ell^\infty(\mathbb{N}, A) \mid \lim_\omega \varphi(a_n^* a_n) = 0\}$ and that $\ell^\infty(\mathbb{N}, A) \subset M^{0,\omega}$. Finally, one defines $A^\omega = (\ell^\infty(\mathbb{N}, A) + I_\omega) / I_\omega \simeq \ell^\infty(\mathbb{N}, A) / I_\omega \cap \ell^\infty(\mathbb{N}, A)$. It follows that A^ω , defined this way, is a von Neumann subalgebra of M^ω , with $E_A^{0,\omega}$ implementing a normal conditional expectation E_{A^ω} that sends the class of $(x_n)_n$ to the class of $(E_A(x_n))_n$. Moreover, by [Popa 1995, Theorem A.1.2], it follows that A^ω is a MASA in M^ω . Note also that E_{A^ω} coincides with E_A when restricted to constant sequences in $M \subset M^\omega$. From the above remark, the ultrapower of $\mathfrak{D} \subset \mathfrak{B}(\ell^2\mathbb{N})$ coincides with $\mathfrak{D} \subset \mathfrak{B}(\ell^2\mathbb{N})$ itself.

Theorem 2.7. *Let M be a von Neumann algebra and $A \subset M$ a MASA with the property that there exists a normal conditional expectation $E_A : M \rightarrow A$. Let ω be a free ultrafilter on \mathbb{N} and denote by $A^\omega \subset M^\omega$ the corresponding ultrapower inclusion.*

- (1) *An element $x \in M_{sa}$ is so-pavable over A if and only if x is app-pavable over A . So, $A \subset M$ has the so-paving property if and only if it has the app-paving property.*
- (2) *Assume that A is countably decomposable. Then $x \in M_{sa}$ is so-pavable over A if and only if x is norm pavable over A^ω . More precisely, if $x \in M_{sa}$ is (ε, n) so-pavable, then x is (ε, n) norm pavable over A^ω ; conversely, if $x \in M_{sa}$ is (ε, n) norm pavable over A^ω , then x is (ε', n) so-pavable for all $\varepsilon' > \varepsilon$.*
- (3) *Still assume that A is countably decomposable. Then the uniform so-paving property of $A \subset M$ is equivalent to the uniform paving property of $A^\omega \subset M^\omega$. More precisely, if every $x \in M_{sa}$ is (ε, n) so-pavable, then every $x \in M_{sa}^\omega$ is (ε, n) norm pavable.*

Proof. (1) follows immediately from Proposition 2.4.

To prove (2) and (3), we assume that A is countably decomposable and it suffices to prove the following two statements for given $0 < \varepsilon < \varepsilon'$ and $n \in \mathbb{N}$:

- If $x \in M_{sa}^\omega$ is represented by the sequence $(x_m) \in M^{0,\omega}$ of self-adjoint elements $x_m \in M_{sa}$ satisfying $\|x_m\| \leq \|x\|$, and if every x_m is (ε, n) so-pavable, then x is (ε, n) norm pavable over A^ω .
- If $x \in M_{sa}$ is (ε, n) norm pavable over A^ω , then x is (ε', n) so-pavable.

Since A is countably decomposable, we can fix a normal faithful state φ on A and still denote by φ its extension $\varphi \circ E_A$ to M . Note that the s^* -topology on the unit ball of M_{sa} coincides with the so -topology, both being implemented by the norm $\|\cdot\|_\varphi$.

We start by proving the first of the two statements above. For every m , the self-adjoint element x_m is (ε, n) so -pavable. So we can take a partition of 1 with projections $p_1^m, \dots, p_n^m \in A$, a projection $q_m \in M$ and an element $a_m \in A$ such that $\|a_m\| \leq \|x_m\| \leq \|x\|$ and such that $\|q_m(\sum_i p_i^m x p_i^m - a_m)q_m\| \leq \varepsilon\|x\|$ and $\varphi(1 - q_m) \leq 2^{-m}$. Since (x_m) and $\ell^\infty(\mathbb{N}, A)$ are both contained in $M^{0,\omega}$, the sequences $((1 - q_m)p_i^m(x_m - a_m)p_i^m)_m$ and $(p_i^m(x_m - a_m)p_i^m(1 - q_m))_m$ belong to I_ω .

Thus, if we let $a = (a_m)$ and $p_i = (p_i^m)_m \in A^\omega$, $1 \leq i \leq n$, then p_1, \dots, p_n is a partition of 1 with projections in A^ω and $p_i(x - a)p_i$ coincides with $(q_m p_i^m(x_m - a_m)p_i^m q_m)_m$ in M^ω . It follows that $\sum_i p_i(x - a)p_i$ coincides with $(q_m \sum_i p_i^m(x_m - a_m)p_i^m q_m)_m$ in M^ω , and thus has norm majorized by $\varepsilon\|x\|$. So we have proved that x is (ε, n) norm pavable over A^ω .

To prove the second of the two statements above, let $x \in M_{\text{sa}}$ be (ε, n) norm pavable over A^ω (as an element in M^ω). Let $\delta > 0$ be arbitrary. We have to prove that there exists an $a' \in A$ with $\|a'\| \leq \|x\|$, a partition of 1 with projections $e_1, \dots, e_n \in A$ and a projection $q \in M$ such that $\varphi(1 - q) \leq \delta$ and $\|q \sum_i e_i(x - a')e_i q\| \leq \varepsilon'\|x\|$.

Take projections $p_1, \dots, p_n \in A^\omega$ and $a \in A_{\text{sa}}^\omega$ such that $\|a\| \leq \|x\|$, $\sum_i p_i = 1$ and $\|\sum_i p_i x p_i - a\| \leq \varepsilon\|x\|$. Represent the p_i by sequences $(p_i^m)_m$ with projections $p_i^m \in A$ such that $\sum_i p_i^m = 1$ for all m , and represent a by a sequence $(a_m)_m$ with $a_m \in A_{\text{sa}}$ and $\|a_m\| \leq \|a\|$ for all m .

We conclude that there exists a sequence of self-adjoint elements $(y_m)_m \in I_\omega$ of norm at most $3\|x\|$ such that the sequence $(b_m)_m = (\sum_i p_i^m(x - a_m)p_i^m - y_m)_m$ satisfies $\|b_m\| \leq \varepsilon\|x\|$ for all m . Since $(y_m)_m \in I_\omega$, we have $\lim_\omega \varphi(|y_m|) = 0$, so that there exists a neighborhood \mathcal{V} of ω such that the spectral projection q_m of $|y_m|$ corresponding to $[0, (\varepsilon' - \varepsilon)\|x\|]$ satisfies $\varphi(1 - q_m) \leq \delta$ for any $m \in \mathcal{V}$. Thus, for any such m , if we let $a' = a_m$, $e_i = p_i^m$ and $q = q_m$, then we have

$$\left\| q \sum_i e_i(x - a')e_i q \right\| \leq \|q_m b_m q_m\| + \|q_m y_m q_m\| \leq \varepsilon\|x\| + (\varepsilon' - \varepsilon)\|x\| \leq \varepsilon'\|x\|. \quad \square$$

Conjecture 2.8. (1) Any MASA in a von Neumann algebra, $A \subset M$, with the property that there exists a normal conditional expectation of M onto A has the so -paving property (equivalently the app -paving property). Also, while the equivalence between so - and app -pavability for an arbitrary MASA A in a von Neumann algebra M is still to be clarified, any MASA $A \subset M$ (not necessarily the range of a normal expectation) ought to satisfy both these properties.

(2) Going even further, we expect that the paving size satisfies the estimate $n_s(x, \varepsilon) \leq C\varepsilon^{-2}$ for all $x \in M_{\text{sa}}$ for some universal constant $C > 0$, independent of $A \subset M$.

Remark 2.9. (i) There is much evidence for 1° in the above conjecture. By Theorem 2.7(3) and the fact that the ultrapower of $\mathcal{D} \subset \mathcal{B}(\ell^2\mathbb{N})$ coincides with $\mathcal{D} \subset \mathcal{B}(\ell^2\mathbb{N})$, so -pavability for this inclusion is equivalent to Kadison–Singer paving, proved to hold true in [Marcus et al. 2015]. It was already noticed in [Popa 2014] that so -pavability over the Cartan MASA of the hyperfinite II_1 factor $D \subset R$ is equivalent to pavability of $\mathcal{D} \subset \mathcal{B}(\ell^2\mathbb{N})$, and thus holds true by [Marcus et al. 2015]. In fact, more cases of the

conjecture can be deduced from [Marcus et al. 2015]. Thus, we note in Section 3 that any MASA in a type I von Neumann algebra (such as a diffuse MASA in $\mathcal{B}(\ell^2\mathbb{N})$) satisfy both *so*- and *app*-pavability. Then in Section 4, we use [Marcus et al. 2015] to prove that any Cartan MASA in an amenable von Neumann algebra, or in a group measure space II_1 factor arising from a free ergodic profinite action, has the *so*-pavability property. On the other hand, the conjecture had already been checked for singular MASAs in II_1 factors in [Popa 2014], and Cyril Houdayer and Yusuke Isono pointed out that, modulo some obvious modifications, the proof in [Popa 2014] works as well for any singular MASA A in an arbitrary von Neumann algebra M , once A is the range of normal conditional expectation from M . Finally, in Remark 5.3, we prove that *so*-pavability also holds for a certain class of MASAs that are neither Cartan, nor singular.

(ii) The estimate on the paving size $n_s(x, \varepsilon) \sim \varepsilon^{-2}$ for all $x \in M_{\text{sa}}$ in point (2) of the conjecture is more speculative, and there is less evidence for it. Based on results in [Popa 2014], we will show in Theorem 5.1 that this estimate does hold true for singular MASAs. We will also show in Proposition 5.4 that this is the best one can expect for the *so*-paving size of any MASA in a II_1 factor, and thus, since $n_s(D \subset R, \varepsilon) = n(\mathcal{D} \subset \mathcal{B}(\ell^2\mathbb{N}), \varepsilon)$, the best one can expect for the paving size in the Kadison–Singer problem as well (a fact already shown in [Casazza et al. 2007]). For the inclusions $\mathcal{D} \subset \mathcal{B}(\ell^2\mathbb{N})$, the order of magnitude of the ε pavings obtained in [Marcus et al. 2015] is $C\varepsilon^{-4}$, but the techniques used there seem to allow obtaining the paving size $C\varepsilon^{-2}$. However, in order to prove Conjecture 2.8 in its full generality, in particular unifying the singular and the Cartan MASA cases (including the diagonal inclusions $D_k \subset \mathcal{B}(\ell_k^2)$, $2 \leq k \leq \infty$), which are quite different in nature, a new idea may be needed.

(iii) The (ε, n) *so*-paving in the case of a MASA $A \subset M$ with a normal conditional expectation $E_A : M \rightarrow A$ and a normal faithful state φ on M with $\varphi \circ E_A = \varphi$ should be compared with (ε, n) L^2 -paving in the Hilbert norm $\|\cdot\|_\varphi$, which, for $x \in M$, $E_A(x) = 0$, requires the existence of a partition of 1 with projections $p_1, \dots, p_n \in A$ such that $\|\sum_i p_i x p_i\|_\varphi \leq \varepsilon \|x\|_\varphi$. This condition is obviously weaker than *so*-paving, with $n(x, \varepsilon) \geq n_s(x, \varepsilon)$ bounded from below by the L^2 -paving size of x for all $x \in M_{\text{sa}}$. It was shown in [Popa 2014, Theorem 3.9] to always occur, with paving size majorised by ε^{-2} (in fact the proof in [Popa 2014] is for MASAs in II_1 factors, but the same proof works in the general case; see also [Popa 1995, Theorem A.1.2] in this respect). The proof of Proposition 5.4 at the end of this paper shows that the paving size is bounded from below by ε^{-2} for all MASAs in II_1 factors.

3. Paving over MASAs in type I von Neumann algebras

Marcus et al. [2015] proved that, for every self-adjoint matrix $T \in M_k(\mathbb{C})$ with zeros on the diagonal and for every $\varepsilon > 0$, there exist r projections $p_1, \dots, p_r \in D_k(\mathbb{C})$ with $r \leq (6/\varepsilon)^4$, $\sum_{i=1}^r p_i = 1$ and $\|p_i T p_i\| \leq \varepsilon \|T\|$ for all i (see also [Tao 2013; Valette 2015] for alternative presentations of the proof). Thus, if \mathcal{D} is the diagonal MASA in $\mathcal{B} = \mathcal{B}(\ell^2\mathbb{N})$, then $\mathcal{D} \subset \mathcal{B}$ has the paving property, with $n(\mathcal{D} \subset \mathcal{B}; x, \varepsilon) \leq 12^4 \varepsilon^{-4}$ for all $x = x^* \in \mathcal{B}$.

In this section, we deduce from this that any MASA A in a type I von Neumann algebra M has the *so*- and *app*-paving property.

We also prove that a MASA A in a von Neumann algebra M with separable predual has the norm paving property if and only if M is of type I and there exists a normal conditional expectation of M onto A .

We start by deducing the following lemma from [Marcus et al. 2015]:

Lemma 3.1. *Let (X, μ) be a standard probability space and $\mathcal{B} = M_k(\mathbb{C})$ or $\mathcal{B} = \mathcal{B}(\ell^2\mathbb{N})$ with the diagonal MASA $\mathcal{D} \subset \mathcal{B}$. Consider the unique normal conditional expectation E of $\mathcal{B} \bar{\otimes} L^\infty(X)$ onto $\mathcal{D} \bar{\otimes} L^\infty(X)$. If $T \in \mathcal{B} \bar{\otimes} L^\infty(X)$ is a self-adjoint element with $E(T) = 0$ and if $\varepsilon > 0$, there exist r projections $p_1, \dots, p_r \in \mathcal{D} \bar{\otimes} L^\infty(X)$ with $r \leq (6/\varepsilon)^4$, $\sum_{i=1}^r p_i = 1$ and $\|p_i T p_i\| \leq \varepsilon \|T\|$ for all i .*

Proof. It suffices to consider $\mathcal{B} = \mathcal{B}(\ell^2\mathbb{N})$. Fix a self-adjoint $T \in \mathcal{B} \bar{\otimes} L^\infty(X)$ with $E(T) = 0$ and $\varepsilon > 0$. Denote by r the largest integer satisfying $r \leq (6/\varepsilon)^4$. We represent T as a Borel function $T : X \rightarrow \mathcal{B}$ satisfying $\|T(x)\| \leq \|T\|$ and $E(T(x)) = 0$ for all $x \in X$. Define Y as the compact Polish space $Y := \{1, \dots, r\}^\mathbb{N}$. For every $y \in Y$ and $i \in \{1, \dots, r\}$, we denote by $p_i^y \in \mathcal{D}$ the projection given by $p_i^y(k) = 1$ if $y(k) = i$ and $p_i^y(k) = 0$ if $y(k) \neq i$. Clearly, the projections p_1^y, \dots, p_r^y with $y \in Y$ describe precisely all partitions of \mathcal{D} . Also, for every $i \in \{1, \dots, r\}$, the map $y \mapsto p_i^y$ is strongly continuous.

Define the Borel map

$$\mathcal{V} : Y \times X \rightarrow [0, +\infty), \quad \mathcal{V}(y, x) = \max_{i=1, \dots, r} \|p_i^y T(x) p_i^y\|$$

and the Borel set $Z \subset Y \times X$ given by $Z := \{(y, x) \in Y \times X \mid \mathcal{V}(y, x) \leq \varepsilon \|T\|\}$. For every $x \in X$, we have that $T(x) \in \mathcal{B}$ with $\|T(x)\| \leq \|T\|$ and $E(T(x)) = 0$. So, by [Marcus et al. 2015], for every $x \in X$ there exists a $y \in Y$ such that $(y, x) \in Z$. Defining $\pi : Y \times X \rightarrow X$ by $\pi(y, x) = x$, this means that $\pi(Z) = X$. By von Neumann’s measurable selection theorem [1949] (or see [Kechris 1995, Theorem 18.1]), we can take a Borel set $X_0 \subset X$ and a Borel function $F : X_0 \rightarrow Y$ such that $\mu(X \setminus X_0) = 0$ and $(F(x), x) \in Z$ for all $x \in X_0$.

The Borel functions $p_i : X_0 \rightarrow \mathcal{D}$, $p_i(x) = p_i^{F(x)}$, then define a partition p_1, \dots, p_r of $\mathcal{D} \bar{\otimes} L^\infty(X)$ with the property that $\|p_i T p_i\| \leq \varepsilon \|T\|$ for all i . □

Proposition 3.2. *Let M be a von Neumann algebra of type I with separable predual and $A \subset M$ an arbitrary MASA. Then $A \subset M$ has both the so- and the app-paving properties.*

More precisely, for every $x \in M_{sa}$ and $\varepsilon > 0$, we have that $n_s(x, \varepsilon) \leq 12^4 \varepsilon^{-4}$. Also, there exists a strongly dense $$ -subalgebra $M_0 \subset M$ with $A \subset M_0$ such that, for every $x \in (M_0)_{sa}$ and $\varepsilon > 0$, we have that $n(x, \varepsilon) \leq 12^4 \varepsilon^{-4}$.*

Proof. Fix an arbitrary MASA $A \subset M$. There exist standard probability spaces $(X_k, \mu_k)_{k \in \mathbb{N}}$ and (X_d, μ_d) , (X_c, μ_c) such that, writing $A_k = L^\infty(X_k)$, and A_d, A_c similarly, the MASA $A \subset M$ is isomorphic to a direct sum of MASAs of the form

$$\begin{aligned} D_k(\mathbb{C}) \otimes A_k &\subset M_k(\mathbb{C}) \otimes A_k, \\ \ell^\infty(\mathbb{N}) \bar{\otimes} A_d &\subset \mathcal{B}(\ell^2(\mathbb{N})) \bar{\otimes} A_d, \\ \text{and } L^\infty([0, 1]) \bar{\otimes} A_c &\subset \mathcal{B}(L^2([0, 1])) \bar{\otimes} A_c. \end{aligned} \tag{3-1}$$

For the first two of these MASAs, by Lemma 3.1, we get that $n(x, \varepsilon) \leq 12^4 \varepsilon^{-4}$ for every self-adjoint element x .

For the rest of the proof, we consider $M = \mathcal{B}(L^2([0, 1])) \bar{\otimes} L^\infty(X)$ and $A = L^\infty([0, 1]) \bar{\otimes} L^\infty(X)$ for some standard probability space (X, μ) . Fix $x \in M_{sa}$ and $\varepsilon > 0$. Let n be the largest integer satisfying $n \leq 12^4 \varepsilon^{-4}$. We prove that x is (ε, n) so-pavable. Choose an so-neighborhood \mathcal{V} of 0 in M . For every $r > 0$, denote by $q_r \in \mathcal{B}(L^2([0, 1]))$ the orthogonal projection on to the subspace $H_r \subset L^2([0, 1])$ defined as

$$H_r = \{\xi \in L^2([0, 1]) \mid \xi \text{ is constant on every interval } [r^{-1}(i-1), r^{-1}i] \text{ for } i = 1, \dots, r\}.$$

Define $\xi_{r,i} = \sqrt{r} \chi_{[r^{-1}(i-1), r^{-1}i]}$, so that $(\xi_{r,i})_{i=1, \dots, r}$ is an orthonormal basis of H_r .

When $r \rightarrow \infty$, we have that $q_r \rightarrow 1$ strongly. So we can fix r large enough such that $1 - (q_r \otimes 1) \in \mathcal{V}$. Denote by $e_i \in L^\infty([0, 1])$ the projection $e_i = \chi_{[r^{-1}(i-1), r^{-1}i]}$. Define the vector functionals ω_{ij} in $\mathcal{B}(L^2([0, 1]))_*$ by $\omega_{ij}(T) = \langle T \xi_{r,i}, \xi_{r,j} \rangle$. Define $a \in A$ by

$$a = \sum_{i=1}^r e_i \otimes (\omega_{ii} \otimes \text{id})(x).$$

By construction, $\|a\| \leq \|x\|$.

Define the isometry $V \in \mathcal{B}(C^r, L^2([0, 1]))$ by $V(\delta_i) = \xi_{r,i}$ for $i = 1, \dots, r$. Define $y \in M_r(\mathbb{C}) \otimes L^\infty(X)$ by $y := (V^* \otimes 1)x(V \otimes 1)$. We also put $b = (V^* \otimes 1)a(V \otimes 1)$. Denoting the natural conditional expectation by $E : M_r(\mathbb{C}) \otimes L^\infty(X) \rightarrow D_r(\mathbb{C}) \otimes L^\infty(X)$, we have $E(y) = b$. By Lemma 3.1, we thus find projections $f_1, \dots, f_n \in D_r(\mathbb{C}) \otimes L^\infty(X)$ such that $f_1 + \dots + f_n = 1$ and $\|f_k(y - b)f_k\| \leq \varepsilon \|y\| \leq \varepsilon \|x\|$ for all $k = 1, \dots, n$.

Define the projections $a_{ki} \in L^\infty(X)$ such that $f_k = \sum_{i=1}^r E_{ii} \otimes a_{ki}$. Then, let $p_k \in A$ be the projections given by $p_k = \sum_{i=1}^r e_i \otimes a_{ki}$. By construction, we have

$$(V^* \otimes 1)p_k x p_k (V \otimes 1) = f_k y f_k \quad \text{for all } k = 1, \dots, n.$$

Therefore,

$$\left\| (q_r \otimes 1) \left(\sum_{k=1}^n p_k x p_k - a \right) (q_r \otimes 1) \right\| = \left\| \sum_{k=1}^n (V^* \otimes 1) p_k x p_k (V \otimes 1) - b \right\| = \left\| \sum_{k=1}^n f_k y f_k - b \right\| \leq \varepsilon \|x\|.$$

Since $1 - (q_r \otimes 1) \in \mathcal{V}$, we have shown that x is (ε, n) so-pavable.

For the final part of the proof, for notational convenience, we replace the interval $[0, 1]$ by the circle \mathbb{T} . We define $M_0 \subset \mathcal{B}(L^2(\mathbb{T}))$ as the $*$ -algebra generated by $L^\infty(\mathbb{T})$ and the periodic rotation unitaries. By construction, $M_0 \subset M$ is a dense $*$ -subalgebra containing A . By Lemma 3.1, every $x \in (M_0)_{sa}$ is $(\varepsilon, 12^4 \varepsilon^{-4})$ pavable for all $\varepsilon > 0$. □

We finally prove that for a MASA A in a von Neumann algebra M with separable predual, the classical Kadison–Singer paving holds if and only if M is of type I and A is the range of a normal conditional expectation.

Theorem 3.3. *Let M be a von Neumann algebra with separable predual and $A \subset M$ a MASA. Then, $A \subset M$ satisfies the norm paving property if and only if M is of type I and A is the range of a normal conditional expectation.*

Also, unless M is of type I and A is the range of a normal conditional expectation, there exist singular conditional expectations of M onto A .

Proof. If M is of type I and A is the range of a normal conditional expectation, then $A \subset M$ is isomorphic to a direct sum of the first two types of MASAs given by (3-1). It then follows from Lemma 3.1 that $A \subset M$ satisfies the norm paving property.

Conversely, assume that $A \subset M$ satisfies the norm paving property. Then there is a unique conditional expectation $E : M \rightarrow A$. By [Akemann and Sherman 2012, Corollary 3.3], this unique conditional expectation E is normal.

Decomposing M as a direct sum of von Neumann algebras of different types, it remains to prove the following: if M has a separable predual and is of type II, type III₁ or type III without a type III₁ direct summand, and if $A \subset M$ is a MASA that is the range of a normal conditional expectation $E : M \rightarrow A$, then there also exists a singular conditional expectation of M onto A . When M is of type II, the existence of a normal conditional expectation of M onto A implies that A is generated by finite projections. By reducing with a projection in A , we may thus assume that M is of type II₁, and, in this case, singular conditional expectations were constructed in [Popa 2014, Remark 2.4.3°] (see also [Popa 1999, Proof of Corollary 4.1.(iii) and Remark 4.3.3°]).

To settle the type III cases, fix a normal faithful state φ on M satisfying $\varphi = \varphi \circ E$. First assume that M is of type III₁ and fix $n \in \mathbb{N}$. We prove that there exist matrix units $\{e_{ij} \mid 1 \leq i, j \leq 2^n\}$ in M such that $\|[\varphi, e_{ij}]\| \leq 8^{-n}$ for all i, j . To prove this statement, we use the following nonfactorial version of the Connes–Størmer transitivity theorem [1978, Theorem 4]: if φ and ρ are normal positive functionals on a type III₁ von Neumann algebra M with separable predual and if $\varphi(a) = \rho(a)$ for all $a \in \mathcal{K}(M)$, then, for every $\varepsilon > 0$, there exists a unitary $u \in M$ such that $\|\varphi - u\rho u^*\| < \varepsilon$.

Since A is diffuse relative to $\mathcal{K}(M) \subset A$, we can choose a partition $e_{ii}, i = 1, \dots, 2^n$, of A satisfying $\varphi(ae_{ii}) = 2^{-n}\varphi(a)$ for all $a \in \mathcal{K}(M)$ and $i = 1, \dots, 2^n$. In particular, the projections e_{ii} have central support 1 and are thus equivalent in M . Put $v_1 = e_{11}$ and choose partial isometries $v_i, i = 2, \dots, 2^n$, such that $v_i v_i^* = e_{11}$ and $v_i^* v_i = e_{ii}$ for all i . Define the positive functionals ψ_i on $e_{11} M e_{11}$ given by $\psi_i(x) = \varphi(v_i^* x v_i)$. Whenever $z \in \mathcal{K}(e_{11} M e_{11})$, write $z = a e_{11}$ with $a \in \mathcal{K}(M)$, so that

$$\psi_i(z) = \varphi(v_i^* a v_i) = \varphi(a v_i^* v_i) = \varphi(a e_{ii}) = 2^{-n} \varphi(a) = \varphi(a e_{11}) = \psi_1(z).$$

By the Connes–Størmer transitivity theorem, we can take unitaries $u_i \in e_{11} M e_{11}$ such that $\|\psi_1 - u_i \psi_i u_i^*\| \leq 8^{-n-1}$ for all i . Replacing v_i by $u_i v_i$, this means that we may assume that $\|\psi_1 - \psi_i\| \leq 8^{-n-1}$ for all i . Define the matrix units $e_{ij} = v_i^* v_j$. Since $\varphi = \varphi \circ E$, we know that $[\varphi, e_{ii}] = 0$ for all i . We then find that $\|[\varphi, e_{ij}]\| \leq 8^{-n}$ for all i, j .

We now proceed as in [Popa 2014, Remark 2.4.3°]. Define the projection $p_n = 2^{-n} \sum_{i,j} e_{ij}$. Since all e_{ii} belong to A , we get that $E(e_{ij}) = \delta_{i,j} e_{ii}$ and thus $E(p_n) = 2^{-n} 1$. Since $\|[\varphi, e_{ij}]\| \leq 8^{-n}$ for all i, j , we also have $\|[\varphi, p_n]\| \leq 4^{-n}$. Define the normal states φ_n on M given by $\varphi_n(x) = 2^n \varphi(p_n x p_n)$, $x \in M$.

Also define the normal functionals η_n on M given by $\eta_n(x) = 2^n \varphi(xp_n)$. Note that $\|\varphi_n - \eta_n\| \leq 2^{-n}$ and that $\eta_n(a) = \varphi(a)$ for all $a \in A$. So, if ψ denotes a weak* limit point of the sequence φ_n in M^* , it follows that ψ is a state on M satisfying $\psi(a) = \varphi(a)$ for all $a \in A$. Defining the projection $q_n = \bigvee_{k=n+1}^\infty p_k$, we get that $\varphi(q_n) \leq 2^{-n}$ and thus $q_n \rightarrow 0$ strongly. By construction, $\psi(1 - q_n) = 0$ for every n . Therefore, ψ is a singular state. Then, averaging ψ by a countable subgroup $\mathcal{U}_0 \subset \mathcal{U}(A)$ with the property that $\mathcal{U}'_0 = A$, we get, as in the proof of [Popa 1999, Corollary 4.1.(iii)], a singular state ψ_0 on M that is A -central and whose restriction to A equals φ . Then $\psi_0 = \varphi \circ \mathcal{E}$, where $\mathcal{E} : M \rightarrow A$ is a singular conditional expectation (see, e.g., [de Korvin 1971]).

Finally, assume that M is of type III but without a direct summand of type III₁. We prove that there exists an intermediate von Neumann algebra $A \subset P \subset M$ such that P is of type II and P is the range of a normal conditional expectation $M \rightarrow P$. (We are grateful to Masamichi Takesaki for useful discussions on the discrete decomposition involved in this part of the proof.) The first part of the proof then shows the existence of singular conditional expectations $P \rightarrow A$, which, composed with the normal expectation of M onto P , provides singular conditional expectations $M \rightarrow A$.

The intermediate type II von Neumann algebra $A \subset P \subset M$ can be constructed using the discrete decomposition for von Neumann algebras of type III _{λ} , $\lambda \in [0, 1)$ (see [Takesaki 2003, Theorems XII.2.1 and XII.3.7]). To avoid the measure-theoretic complications of a direct integral decomposition of M , we use the following “global” discrete decomposition. Denote by $(\sigma_t)_{t \in \mathbb{R}}$ the modular automorphism group of φ and by $N = M \rtimes_{\sigma} \mathbb{R}$ the continuous core of M (see [Takesaki 2003, Theorem XII.1.1]). Denote by $(\theta_t)_{t \in \mathbb{R}}$ the dual action of \mathbb{R} on N . Write $\mathcal{X}(N) = L^\infty(Z, \mu)$, where (Z, μ) is a standard probability space. Note that θ restricts to a nonsingular action of \mathbb{R} on (Z, μ) . The assumption that M has no direct summand of type III₁ is reflected by the possibility of choosing Z in such a way that no $x \in Z$ is stabilized by all $t \in \mathbb{R}$. This means that the flow $\mathbb{R} \curvearrowright (Z, \eta)$ can be built as a flow under a ceiling function (i.e., a nonergodic version of [Takesaki 2003, Theorem XII.3.2]). More concretely, we find a nonsingular action of $\mathbb{Z} \times \mathbb{R}$ on a standard probability space Ω with the following properties:

- The actions of \mathbb{Z} and \mathbb{R} on Ω are separately free and proper, that is, $\mathbb{Z} \curvearrowright \Omega$ is conjugate with $\mathbb{Z} \curvearrowright \Omega_0 \times \mathbb{Z}$ given by $n \cdot (x, m) = (x, n + m)$, and $\mathbb{R} \curvearrowright \Omega$ is conjugate with $\mathbb{R} \curvearrowright \Omega_1 \times \mathbb{R}$ given by $t \cdot (y, s) = (y, t + s)$.
- The action $\mathbb{R} \curvearrowright Z$ is conjugate with $\mathbb{R} \curvearrowright \Omega/\mathbb{Z}$. So, we can identify $\Omega_0 = Z$ and thus $\Omega = Z \times \mathbb{Z}$ with the action $\mathbb{R} \curvearrowright \Omega$ given by $t \cdot (x, n) = (t \cdot x, \omega(t, x) + n)$, where $\omega : \mathbb{R} \times Z \rightarrow \mathbb{Z}$ is a 1-cocycle.

Since $L^\infty(Z) = \mathcal{X}(N)$, the 1-cocycle ω gives rise to a natural action $\mathbb{R} \curvearrowright N \overline{\otimes} \ell^\infty(\mathbb{Z})$. We define $\mathcal{N} := (N \overline{\otimes} \ell^\infty(\mathbb{Z})) \rtimes \mathbb{R}$ and consider the action $\mathbb{Z} \curvearrowright \mathcal{N}$ given by translation on $\ell^\infty(\mathbb{Z})$ and the identity on N and $L(\mathbb{R})$. As in [Takesaki 2003, Lemma XII.3.5], it follows that \mathcal{N} is of type II and that $\mathcal{N} \rtimes \mathbb{Z}$ is naturally isomorphic with $M \overline{\otimes} \mathcal{B}(L^2(\mathbb{R})) \overline{\otimes} \mathcal{B}(L^2(\mathbb{Z}))$.

Since $\varphi = \varphi \circ E$, we get that every $a \in A$ belongs to the centralizer of φ . We can then view $A \overline{\otimes} L(\mathbb{R})$ as a MASA of $N = M \rtimes_{\sigma} \mathbb{R}$. Also $\mathcal{X}(N) \subset A \overline{\otimes} L(\mathbb{R})$. So, the above action $\mathbb{R} \curvearrowright N \overline{\otimes} \ell^\infty(\mathbb{Z})$ globally preserves $A \overline{\otimes} L(\mathbb{R}) \overline{\otimes} \ell^\infty(\mathbb{Z})$. We can then define $\mathcal{A} := (A \overline{\otimes} L(\mathbb{R}) \overline{\otimes} \ell^\infty(\mathbb{Z})) \rtimes \mathbb{R}$ as a von Neumann subalgebra of \mathcal{N} .

The dual action $\mathbb{R} \curvearrowright L(\mathbb{R})$ is conjugate with the translation action $\mathbb{R} \curvearrowright L^\infty(\mathbb{R})$. Therefore, the 1-cocycle ω trivializes on $A \bar{\otimes} L(\mathbb{R})$. This yields the natural surjective $*$ -isomorphism

$$\Psi : A \bar{\otimes} \mathcal{B}(L^2(\mathbb{R})) \bar{\otimes} \ell^\infty(\mathbb{Z}) \rightarrow \mathcal{A}.$$

Choose a minimal projection $q \in \mathcal{B}(L^2(\mathbb{R})) \bar{\otimes} \ell^\infty(\mathbb{Z})$ and put $p = \Psi(1 \otimes q)$. We then get that $A \subset p\mathcal{N}p \subset p(\mathcal{N} \rtimes \mathbb{Z})p$. Using the natural isomorphism of $\mathcal{N} \rtimes \mathbb{Z}$ with $M \bar{\otimes} \mathcal{B}(L^2(\mathbb{R})) \bar{\otimes} \mathcal{B}(\ell^2(\mathbb{Z}))$, we can identify $p(\mathcal{N} \rtimes \mathbb{Z})p = M$ and have found $p\mathcal{N}p$ as an intermediate type II von Neumann algebra sitting between A and M . Because there is a natural normal conditional expectation of $\mathcal{N} \rtimes \mathbb{Z}$ onto \mathcal{N} , we also have a normal conditional expectation of M onto $p\mathcal{N}p$. \square

4. Paving over Cartan subalgebras

The paving property for the diagonal MASA $\mathcal{D} \subset \mathcal{B}(\ell^2\mathbb{N})$ was shown in [Popa 2014] to be equivalent to the paving property for the ultrapower inclusion $D^\omega \subset R^\omega$, where D is the Cartan MASA in the hyperfinite II_1 factor R . As we have seen in Theorem 2.7, this is equivalent, in turn, to the (uniform) *so*-paving property for $D \subset R$. Thus, [Marcus et al. 2015] implies that *so*-paving holds true for $D \subset R$. We will now use [Marcus et al. 2015] to prove that, in fact, *so*-paving holds true for any Cartan subalgebra of an amenable von Neumann algebra as well as for Cartan inclusions arising from a free ergodic profinite probability measure-preserving (pmp) action of a countable group, $\Gamma \curvearrowright X$, i.e., $A = L^\infty(X) \subset L^\infty(X) \rtimes \Gamma = M$.

Theorem 4.1. (1) *If M is an amenable von Neumann algebra and $A \subset M$ is a Cartan MASA of M , then $A \subset M$ has the *so*-paving property, with $n_s(A \subset M; x, \varepsilon) \leq 25^4 \varepsilon^{-4}$ for all $x \in M_{\text{sa}}$.*

(2) *Let Γ be a countable group and $\Gamma \curvearrowright (X, \mu)$ an essentially free, ergodic, pmp action that is profinite. Then $A = L^\infty(X) \subset L^\infty(X) \rtimes \Gamma = M$ is *so*-pavable and, for every $x \in M_{\text{sa}}$, $n_s(A \subset M; x, \varepsilon) \leq 13^4 \varepsilon^{-4}$. So, also, $A^\omega \subset M^\omega$ satisfies the norm paving property and, for every $x \in M_{\text{sa}}^\omega$, $n(A^\omega \subset M^\omega; x, \varepsilon) \leq 13^4 \varepsilon^{-4}$.*

Proof. (1) By [Connes et al. 1981], given any $x \in M_{\text{sa}}$ and any *so*-neighborhood \mathcal{V} of 0, there exists a finite-dimensional von Neumann subalgebra $B_0 \subset M$, having the diagonal A_0 contained in A and $\mathcal{N}_{B_0}(A_0) \subset \mathcal{N}_M(A)$, and an element $y_0 = y_0^* \in B_0$, $\|y_0\| \leq \|x\|$, such that $x - y_0 \in \mathcal{V}$. But, by [Marcus et al. 2015] (see Lemma 3.1), y_0 can be (ε_0, n) paved over A_0 (thus also over $A \supset A_0$) for some ε_0 slightly smaller than $\varepsilon/2$ and $n \leq 25^4 \varepsilon^{-4}$. By Proposition 2.4, we conclude that x can be (ε, n) *so*-paved for every $\varepsilon > 0$.

(2) Take a decreasing sequence of finite-index subgroups $\Gamma_n < \Gamma$ such that (X, μ) is the inverse limit of the spaces Γ/Γ_n equipped with the normalized counting measure. Write $r_n : X \rightarrow \Gamma/\Gamma_n$. The essential freeness of $\Gamma \curvearrowright (X, \mu)$ means that, for every $g \in \Gamma - \{e\}$, we have

$$\lim_n \frac{|\{x \in \Gamma/\Gamma_n \mid gx = x\}|}{[\Gamma : \Gamma_n]} = 0. \tag{4-1}$$

Write $A_n = \ell^\infty(\Gamma/\Gamma_n)$. View $A_1 \subset A_2 \subset \dots$ as an increasing sequence of subalgebras of A with dense union. Fix a free ultrafilter ω on \mathbb{N} . For every $n \in \mathbb{N}$, define $M_n \cong M_{[\Gamma, \Gamma_n]}(\mathbb{C})$ as the matrix algebra with entries indexed by elements of Γ/Γ_n . Consider $A_n \subset M_n$ as the diagonal subalgebra. For $g \in \Gamma$, denote

by $u_{g,n} \in M_n$ the corresponding permutation unitary. Denote by τ_n the normalized trace on M_n and by $\|\cdot\|_2$ the corresponding 2-norm. By (4-1), we have that $\|E_{A_n}(u_{g,n})\|_2 \rightarrow 0$ for all $g \in \Gamma - \{e\}$.

Denote by $\mathcal{M} = \prod_{\omega}(M_n, \tau_n)$ the ultraproduct of the matrix algebras M_n , with MASA $\mathcal{A} \subset \mathcal{M}$ defined as $\mathcal{A} = \prod_{\omega} A_n$. We can then define a normal faithful $*$ -homomorphism $\pi : M \rightarrow \mathcal{M}$, where $\pi(au_g) \in \mathcal{M}$ is represented by the sequence $(au_{g,n})_{n \geq m}$ whenever $a \in A_m$.

Fix $\varepsilon > 0$ and denote by r the largest integer that is smaller than or equal to $(12/\varepsilon)^4$. We claim that, for every self-adjoint $x \in M^{\omega}$, there exists a partition p_1, \dots, p_r of A^{ω} such that $\|p_i(x - E_{A^{\omega}}(x))p_i\| \leq \varepsilon\|x\|$ for all i . To prove this claim, it suffices to prove the following local statement: for every self-adjoint $x \in M$ with $\|x\| \leq 1$, and for all $\delta > 0$, $m \in \mathbb{N}$, there exists a partition p_1, \dots, p_r of A (thus independent of m and δ , since r was fixed in the beginning) such that the element $y = \sum_{i=1}^r p_i(x - E_A(x))p_i$ satisfies

$$|\tau(y^k)| \leq \varepsilon^k + \delta \quad \text{for all } k = 1, \dots, m. \tag{4-2}$$

Indeed, once this local statement is proved and given a self-adjoint element $x \in M^{\omega}$ represented by a sequence $(x_m)_m$ with $x_m = x_m^*$ and $\|x_m\| \leq \|x\|$ for all m , we find partitions p_1^m, \dots, p_r^m of A such that the elements $y_m = \sum_{i=1}^r p_i^m(x_m - E_A(x_m))p_i^m$ satisfy

$$|\tau(y_m^k)| \leq (\varepsilon\|x_m\|)^k + \frac{1}{m} \leq (\varepsilon\|x\|)^k + \frac{1}{m} \quad \text{for all } k = 1, \dots, m.$$

Defining the projections $p_i \in A^{\omega}$ by the sequences $p_i = (p_i^m)_m$ and putting $y = \sum_{i=1}^r p_i(x - E_{A^{\omega}}(x))p_i$, this means that $|\tau(y^k)| \leq (\varepsilon\|x\|)^k$ for all $k \in \mathbb{N}$. Since y is self-adjoint, it follows from the spectral radius formula that $\|y\| \leq \varepsilon\|x\|$, so that the claim is proved. This means that every self-adjoint $x \in M^{\omega}$ can be (ε, n) paved for some $n \leq 12^4\varepsilon^{-4}$. So, by Theorem 2.7, also every $x \in M_{\text{sa}}$ can be (ε, n) so-paved for some $n \leq 13^4\varepsilon^{-4}$.

We now deduce the above local statement from [Marcus et al. 2015]. Fix $x \in M_{\text{sa}}$ with $\|x\| \leq 1$ and fix $\delta > 0$ and $m \in \mathbb{N}$. By the Kaplansky density theorem, we can take $n_0 \in \mathbb{N}$, a finite subset $\mathcal{F} \subset \Gamma$ and a self-adjoint $x_0 \in \text{span}\{au_g \mid a \in A_{n_0}, g \in \mathcal{F}\}$ with $\|x_0\| \leq 1$ and $\|x - x_0\|_2 \leq \delta/(m2^m)$. We may assume that $e \in \mathcal{F}$. We prove below that we can find a partition p_1, \dots, p_r of A such that the element $y_0 := \sum_{i=1}^r p_i(x_0 - E_A(x_0))p_i$ satisfies $|\tau(y_0^k)| \leq \varepsilon^k + \delta/2$ for all $k = 1, \dots, m$. Writing $y := \sum_{i=1}^r p_i(x - E_A(x))p_i$, we find that $\|y - y_0\|_2 \leq \|x - x_0\|_2$ and also $\|y\| \leq 2$, $\|y_0\| \leq 2$. Therefore,

$$\|y^k - y_0^k\|_2 \leq m2^{m-1}\|x - x_0\|_2 \leq \frac{\delta}{2} \quad \text{for all } k = 1, \dots, m.$$

Thus $|\tau(y^k) - \tau(y_0^k)| \leq \delta/2$, so that (4-2) follows.

We now must find a good paving for x_0 . For this, we use the ultraproduct \mathcal{M} and the injective homomorphism $\pi : M \rightarrow \mathcal{M}$ defined above. Write $x_0 = \sum_{g \in \mathcal{F}} a_g u_g$ with $a_g \in A_{n_0}$. Then, $\pi(x_0)$ is represented by the bounded sequence of self-adjoint elements $T_n := \sum_{g \in \mathcal{F}} a_g u_{g,n}$. Since $\|\pi(x_0)\| = \|x_0\| \leq 1$, we can take a bounded sequence of self-adjoint elements $S_n \in M_n$ such that $\lim_{n \rightarrow \omega} \|S_n\|_2 = 0$ and $\|T_n - S_n\| \leq 1$ for all n . Take $K > 0$ such that $\|T_n\| \leq K$ and $\|S_n\| \leq K$ for all n . Take $n_1 \geq n_0$ close enough to ω such that $\|S_{n_1}\|_2 \leq \delta/(4m(2K)^{m-1})$ and such that (using (4-1)) the projection $q \in A_{n_1}$

defined by the set

$$\{x \in \Gamma / \Gamma_{n_1} \mid gx \neq x \text{ for all } g \in \mathcal{F}^m \setminus \{e\}\}$$

satisfies $\|1 - q\|_2 \leq \delta/2^{m+2}$. Write $R = T_{n_1} - S_{n_1}$. Since $R = R^*$ and $\|R\| \leq 1$, by [Marcus et al. 2015], there exists a partition p_1, \dots, p_r of A_{n_1} such that the element $Y := \sum_{i=1}^r p_i (R - E_{A_{n_1}}(R)) p_i$ satisfies

$$\|Y\| \leq \frac{1}{2} \varepsilon \|R - E_{A_{n_1}}(R)\| \leq \varepsilon.$$

We define $Z := \sum_{i=1}^r p_i (T_{n_1} - E_{A_{n_1}}(T_{n_1})) p_i$. Note that $\|Y\| \leq 2$ and $\|Z\| \leq 2K$. Also, $\|Y - Z\|_2 \leq \|S_{n_1}\|_2$, so that, for all $k = 1, \dots, m$, we have

$$\|Y^k - Z^k\|_2 \leq m(2K)^{m-1} \|S_{n_1}\|_2 \leq \frac{\delta}{4}.$$

Then also $\|Y^k q - Z^k q\|_2 \leq \delta/4$. Because $\|Y^k q\| \leq \|Y\|^k \leq \varepsilon^k$, we conclude that

$$|\tau_{n_1}(Z^k q)| \leq \varepsilon^k + \frac{\delta}{4} \text{ for all } k = 1, \dots, m.$$

By our choice of q , whenever $1 \leq k \leq m$, $a_1, \dots, a_k \in A_{n_1}$ and $g_1, \dots, g_k \in \mathcal{F}$, we have

$$\tau_{n_1}(a_1 u_{g_1, n_1} \cdots a_k u_{g_k, n_k} q) = \tau(a_1 u_{g_1} \cdots a_k u_{g_k} q),$$

where the left-hand side uses the trace in M_{n_1} , while the right-hand side uses the trace in M . Writing $y_0 = \sum_{i=1}^r p_i (x_0 - E_A(x_0)) p_i$, we find that

$$|\tau(y_0^k q)| = |\tau_{n_1}(Z^k q)| \leq \varepsilon^k + \frac{\delta}{4} \text{ for all } k = 1, \dots, m.$$

Since $\|y_0^k q - y_0^k\|_2 \leq 2^m \|q - 1\|_2 \leq \delta/4$, we get the required estimate

$$|\tau(y_0^k)| \leq \varepsilon^k + \frac{\delta}{2} \text{ for all } k = 1, \dots, m. \quad \square$$

Remark 4.2. We believe that [Marcus et al. 2015] can be used to settle Conjecture 2.8 (*so*-pavability) for all Cartan subalgebras in II_1 factors $A \subset M$, and in fact for any Cartan subalgebra in a von Neumann algebra. The following could be an approach to a solution, but we could not make it work. Consider the abelian von Neumann algebra $\mathcal{A} = A \vee JAJ$ acting on $L^2(M)$. This is a MASA in $\mathcal{M} = \langle M, e_A \rangle = (JAJ)' \cap \mathcal{B}(L^2(M))$ and there exists a normal conditional expectation from the type I von Neumann algebra \mathcal{M} onto \mathcal{A} (see [Feldman and Moore 1977]). Therefore, $\mathcal{A} \subset \mathcal{M}$ satisfies the norm-paving property. If, now, $x \in M$, we can pave x by a partition $p_i \in A \vee JAJ$. Taking a very fine partition $q_j \in A$, we can *so*-approximate p_i by $\sum_j p_{i,j} Jq_j J$. It should be possible to choose the $p_{i,j}$ as “almost partitions” of 1 in A such that, for many j (or at least one j), the $p_{1,j}, \dots, p_{r,j}$ approximately pave x (in the *so*-paving sense).

In relation to the approach to proving *so*-pavability for Cartan subalgebras suggested above, let us mention that the [Marcus et al. 2015] paving property for discrete MASAs in type I von Neumann algebras allows the following new characterization for a MASA to be Cartan:

Corollary 4.3. *Let M be a von Neumann algebra with separable predual and $A \subset M$ a MASA in M that is the range of a normal conditional expectation. Let $\mathcal{M} = \langle M, e_A \rangle = (JAJ)' \cap \mathcal{B}(L^2 M)$ and $\mathcal{A} = A \vee JAJ$.*

The following conditions are equivalent:

- (1) A is a Cartan subalgebra of M .
- (2) \mathcal{A} is a Cartan subalgebra of \mathcal{M} .
- (3) $\mathcal{A} \subset \mathcal{M}$ has the paving property.

Proof. The equivalence of (1) and (2) follows from [Feldman and Moore 1977]. Since \mathcal{M} is of type I, a MASA in \mathcal{M} is a Cartan subalgebra if and only if it is the range of a normal conditional expectation. Also, an abelian subalgebra of \mathcal{M} can only satisfy the paving property if it is maximal abelian. Therefore, the equivalence of (2) and (3) follows from Theorem 3.3 (and, thus, uses [Marcus et al. 2015]). \square

5. Paving size for one or more elements

In [Marcus et al. 2015], it is shown that every self-adjoint element T in $\mathcal{B}(\ell_k^2)$, $1 \leq k \leq \infty$, can be $(\varepsilon, 12^4\varepsilon^{-4})$ paved over its diagonal MASA. In the previous section, we have used this result to prove that any amenable von Neumann algebra M with a Cartan subalgebra $A \subset M$ is $(\varepsilon, 25^4\varepsilon^{-4})$ so -pavable over A ; equivalently, any self-adjoint element in M^ω is $(\varepsilon, 25^4\varepsilon^{-4})$ norm pavable over A^ω .

On the other hand, it has been shown in [Popa 2014] that, if A is a singular MASA in a II_1 factor M , then $n(A^\omega \subset M^\omega; x, \varepsilon) \leq 25^2\varepsilon^{-2}(\varepsilon^{-1} + 1) \leq 1250\varepsilon^{-3}$ for all $x \in M_{\text{sa}}^\omega$. Or, equivalently, $n_s(A \subset M; x, \varepsilon) \leq 1250\varepsilon^{-3}$ for all $x \in M_{\text{sa}}$ (see [Popa 2014], Corollary 4.3 and the last lines of the proof of Proposition 2.3). This is shown by first proving that, given any $\varepsilon > 0$ and any finite set of projections in M that have scalar expectation onto A , one can find a simultaneous so -paving for all of them with at most $2\varepsilon^{-2}$ projections in A (see [Popa 2014, Corollary 4.2]), then using a dilation argument to deduce it for arbitrary self-adjoint elements.

We will now show that, in fact, the so -paving size for self-adjoint elements over singular MASAs, and respectively the norm-paving size over an ultraproduct of singular MASAs, can be improved to $4^2\varepsilon^{-2}$ (the order of magnitude ε^{-2} for the paving size is optimal; see Proposition 5.4 below). Moreover, we show that one can (ε, n) so -pave simultaneously any number of self-adjoint elements with $n < 1 + 4^2\varepsilon^{-2}$ many projections over a singular MASA, a phenomenon that does not occur in the classical Kadison–Singer case $\mathcal{D} \subset \mathcal{B}(\ell^2\mathbb{N})$, nor in fact for any Cartan subalgebra in a II_1 factor $A \subset M$ (see Remark 5.2 below). The proof combines the uniform paving of projections that have scalar expectation onto A in [Popa 2014, Corollary 4.2] with a better dilation argument that allows us not to lose on the paving size, while still dealing simultaneously with several self-adjoint elements.

Theorem 5.1. *Let $A_n \subset M_n$ be a sequence of singular MASAs in finite von Neumann algebras. Put $\mathbf{M} = \prod_\omega M_n$ and $\mathbf{A} = \prod_\omega A_n$.*

Let $\varepsilon > 0$. For every finite set of self-adjoint elements $\mathcal{F} \subset \mathbf{M} \ominus \mathbf{A}$, there exists a decomposition of the identity $1 = p_1 + \cdots + p_n$ with $n < 1 + 16\varepsilon^{-2}$ projections $p_j \in \mathbf{A}$ such that

$$\left\| \sum_{j=1}^n p_j x p_j \right\| \leq \varepsilon \|x\| \quad \text{for all } x \in \mathcal{F}.$$

Proof. Fix $\varepsilon > 0$ and let n be the unique integer satisfying $16\varepsilon^{-2} \leq n < 1 + 16\varepsilon^{-2}$. Also fix a finite subset $\{x_1, \dots, x_m\} \subset M \ominus A$ of self-adjoint elements. We may assume that $\|x_k\| = 1$ for all k . Define $y_k = (1 + x_k)/2$. Note that $0 \leq y_k \leq 1$ and $E_A(y_k) = \frac{1}{2}$. Let (B, τ) be any diffuse abelian von Neumann algebra. Write

$$\tilde{M} = \prod_{\omega} (M_2(\mathbb{C}) \otimes (M_n * B))$$

and consider the von Neumann subalgebra $\tilde{A} \subset \tilde{M}$ given by

$$\tilde{A} = \prod_{\omega} (A_n \oplus B) = A \oplus B^{\omega}.$$

Note that, for every n , we have that $A_n \oplus B \subset M_2(\mathbb{C}) \otimes (M_n * B)$ is a singular MASA. Therefore, $\tilde{A} \subset \tilde{M}$ is the ultraproduct of a sequence of singular MASAs.

Define the orthogonal projections $Q_k \in \tilde{M}$ given by

$$Q_k = \begin{pmatrix} y_k & \sqrt{y_k - y_k^2} \\ \sqrt{y_k - y_k^2} & 1 - y_k \end{pmatrix}.$$

Note that $E_{\tilde{A}}(Q_k) = \frac{1}{2}$.

Applying [Popa 2014, Theorem 4.1.(a)] to $X = \{Q_k - \frac{1}{2} \mid k = 1, \dots, m\}$, we find a diffuse von Neumann subalgebra $B_0 \subset \tilde{A}$ such that every product with factors alternatingly from $B_0 \ominus \mathbb{C}1$ and X has zero expectation on \tilde{A} . In particular, for all k , we have that B_0 and $\mathbb{C}1 + \mathbb{C}Q_k$ are free von Neumann subalgebras of (\tilde{M}, τ) .

Choose any decomposition of the identity $1 = P_1 + \dots + P_n$ with n projections $P_j \in B_0$ satisfying $\tau(P_j) = 1/n$. Fix $j \in \{1, \dots, n\}$ and $k \in \{1, \dots, m\}$. Since the projections P_j and Q_k are free, with traces respectively given by $1/n$ and $\frac{1}{2}$, it follows from [Voiculescu 1987, Example 2.8] that

$$\|P_j Q_k P_j - \frac{1}{2} P_j\| \leq \frac{2}{\sqrt{n}}.$$

Write $P_j = p_j \oplus q_j$, where $p_j \in A$ and $q_j \in B^{\omega}$ are projections. The upper left corner of $P_j Q_k P_j - \frac{1}{2} P_j$ equals $p_j(x_k/2)p_j$, and we conclude that

$$\|p_j x_k p_j\| \leq \frac{4}{\sqrt{n}} \leq \varepsilon.$$

This ends the proof. □

Remark 5.2. (1) As shown in Theorem 5.1 above, in the case that $A \subset M$ is singular, any finite number of elements can be simultaneously (ε, n) norm paved over A^{ω} with $n < 1 + 16\varepsilon^{-2}$. By [Popa 2014, Theorem 3.7], any finite number of elements can also be simultaneously (ε, n) L^2 -paved over A^{ω} with $n < 1 + \varepsilon^{-2}$. But this is no longer true for norm paving over a MASA that has “large normalizer”. For instance, one cannot pave multiple matrices in $\mathcal{B}(\ell^2\mathbb{N})$ over its diagonal \mathcal{D} . This can be seen as follows: Assume M is a finite von Neumann algebra and $A \subset M$ is a MASA whose normalizer $\mathcal{N}_M(A)$ generates a II_1 von Neumann algebra. Then, for any $m \geq 1$, there exists a unitary $u \in \mathcal{N}_M(A)$ such that $E_A(u^k) = 0$ for

all $1 \leq k \leq m - 1$, $u^m = 1$. Denote by σ the automorphism $\text{Ad}(u)$ of A . Assume now that p_1, \dots, p_n is a partition of A that simultaneously c paves the set of $m - 1$ unitaries $\{u^k \mid k = 1, \dots, m - 1\}$ for some $0 < c < 1$. Then $\|p_i u^k p_i\| \leq c$ for all $i = 1, \dots, n$ and all $k = 1, \dots, m - 1$. But $\|p_i u^k p_i\| = \|p_i \sigma^k(p_i)\|$ and $p_i \sigma^k(p_i)$ is a projection. Thus, $p_i \sigma^k(p_i)$ must be zero for all i and k . So, for every fixed i , we find that $p_i, \sigma(p_i), \dots, \sigma^{m-1}(p_i)$ are orthogonal. Thus, $\tau(p_i) \leq 1/m$. Since $\sum_i p_i = 1$, it follows that $n \geq m$. Note that, by replacing the cyclic group $\mathbb{Z}/m\mathbb{Z} \simeq \{u^k \mid 0 \leq k \leq m - 1\} \subset \mathcal{N}_M(A)$ with the group $(\mathbb{Z}/2\mathbb{Z})^t \hookrightarrow \mathcal{N}_M(A)$, acting freely on A , one gets the same result for $m = 2^t$, but with a set of $m - 1$ self-adjoint unitaries.

We conclude that if the normalizer of a MASA generates a type II_1 von Neumann algebra then, given any m , there exists a set of $m - 1$ unitaries in M such that, in order to simultaneously c pave all of them, with $c < 1$, we need at least m projections (in the case $m = 2^t$, the set can be taken of self-adjoint unitaries). Note that, if $u \in \mathcal{N}_M(A)$ is as before and we let $X = \{(u^k + u^{-k})/2, (u^k - u^{-k})/(2i) \mid 1 \leq k \leq m - 1\}$, then any partition of 1 with projections $p_1, \dots, p_n \subset A$ that simultaneously $(c/2)$ paves all $x \in X$ must satisfy $n \geq m = |X|/2 + 1$. Thus, under the same assumptions on $A \subset M$ as before, given any m_0 and any $c_0 < \frac{1}{2}$, there exists a set $X_0 \subset M_{\text{sa}}$ with $|X_0| = m_0$ such that, in order to simultaneously c_0 pave all $x \in X_0$, we need at least $m_0/2$ projections.

(2) If $A \subset M$ is a MASA in a von Neumann algebra, $X \subset M$ and $\varepsilon > 0$, we define $n(A \subset M; X, \varepsilon)$ in the obvious way. Also, for m a positive integer, we let $n(A \subset M; m, \varepsilon) = \sup\{n(A \subset M; X, \varepsilon) \mid X \subset M_{\text{sa}}, |X| = m\}$, and call it the *multipaving size* of $A \subset M$. One always has the estimate $n(A \subset M; m, \varepsilon) \leq n(A \subset M; \varepsilon)^m$. By Theorem 5.1, if A is a singular MASA in a II_1 factor M , then $n(A^\omega \subset M^\omega; m, \varepsilon) < 1 + 16\varepsilon^{-2}$ for all $m \geq 1$, $\varepsilon > 0$. By 5.2.1° above, if $\mathcal{N}_M(A)''$ is of type II_1 , then $n(A \subset M; m - 1, c) \geq m$ for all $m = 2^t$, $0 < c < 1$, while for arbitrary m_0 (not of the form 2^t) and $c_0 < \frac{1}{2}$, we have $n(A \subset M; m_0, c_0) \geq m_0/2$. At the same time, by [Marcus et al. 2015], we have $n(A \subset M; m, \varepsilon) \leq (12/\varepsilon)^{4m}$.

It would be interesting to find estimates for this multipaving size in this last case (when $\mathcal{N}_M(A)$ is large). By arguing as in the proof of [Popa 2014, Theorem 2.2], we see that $n(\mathfrak{D} \subset \mathfrak{B}; m, \varepsilon) = n(D^\omega \subset R^\omega; m, \varepsilon) = n(\mathbf{D} \subset \mathbf{M}; m, \varepsilon)$ for all $\varepsilon > 0$, $m \in \mathbb{N}$, where $\mathbf{D} \subset \mathbf{M}$ denotes the ultraproduct inclusion $\prod_\omega D_k \subset \prod_\omega M_{k \times k}(\mathbb{C})$. Thus, estimating the multipaving size for $D^\omega \subset R^\omega$, or for $\mathbf{D} \subset \mathbf{M}$, is the same as doing it for $\mathfrak{D} \subset \mathfrak{B}$. From Remark 5.2(1) and [Marcus et al. 2015], for each fixed $1 > \varepsilon > 0$, the growth in m of the multiple paving size $n(\mathfrak{D} \subset \mathfrak{B}; m, \varepsilon)$ is between m and $(\varepsilon^{-4})^m$. Calculating its order of magnitude seems a very challenging problem. It would already be interesting to decide whether this growth is linear (more generally, polynomial), or exponential.

Remark 5.3. Exactly the same proof as that of [Popa 2014, Theorem 4.1.(a)] shows the following more general result. Let (M, τ) be a von Neumann algebra with a normal faithful tracial state, $A \subset M$ a MASA in M and $A \subset N \subset M$ an intermediate von Neumann subalgebra with the following malnormality property: the only A - N -subbimodule of $L^2(M \ominus N)$ that is finitely generated as a right N -module is $\{0\}$. Then, given any $\|\cdot\|_2$ -separable subspace $X \subset M \ominus N$ and any free ultrafilter ω on \mathbb{N} , there exists a diffuse von Neumann subalgebra $B_0 \subset A^\omega$ such that every “word” with alternating “letters” from $B_0 \ominus \mathbb{C}1$ and X has trace zero. Note that [Popa 2014, Theorem 4.1.(a)] corresponds to the case $N = A$ because,

by [Popa 2006, Section 1.4], the singularity of A in M implies that $L^2(M \ominus A)$ contains no nonzero A - A -subbimodule that is finitely generated as a right A -module.

By combining this result with the dilation argument as in the proof of Theorem 5.1 above, it follows that any $x \in M \ominus N$ can be so -paved, with $n_s(A \subset M; x, \varepsilon) < 5^2 \varepsilon^{-2}$. Thus, if $A \subset N$ satisfies the so -paving property, then so does $A \subset M$, and we have the estimate $n_s(A \subset M; \varepsilon) \leq 20^2 \varepsilon^{-2} n_s(A \subset N; \varepsilon/2)$.

This observation allows us to derive the so -paving property (and thus the validity of Conjecture 2.8(1) for a class of MASAs that are neither singular nor Cartan. More precisely, assume that $A \subset M$ is a MASA in a II_1 factor such that the normalizer $\mathcal{N}_M(A)$ generates a von Neumann algebra N satisfying the conditions: (1) either N is amenable, or $A \subset N$ can be obtained as a group measure space construction from a free ergodic profinite action of a countable group; (2) $N \subset M$ satisfies the above malnormality condition. Then, $A \subset M$ has the so -paving property.

Concrete such examples can be easily derived from [Popa 1983]. For instance, [Popa 1983, Theorem 5.1] provides an example of a MASA A in the hyperfine II_1 factor $M \simeq R$ such that the normalizer of A in M generates a subfactor $N \subset M$ with the property that ${}_N L^2(M \ominus N)_N$ is an infinite multiple of the coarse N - N -bimodule $L^2(N) \otimes L^2(N)$, and thus $N \subset M$ satisfies the malnormality condition. Other examples come from free product constructions: let $A \subset N$ be a Cartan subalgebra of a (separable) amenable von Neumann algebra of type II_1 (e.g., the hyperfinite II_1 factor, $N \simeq R$); let (B, τ) be a diffuse finite von Neumann algebra and denote $M = N * B$; then, A is a MASA in M , the normalizer of A in M generates N , and again, by [Popa 1983, Remark 6.3], ${}_N L^2(M \ominus N)_N$ is an infinite multiple of the coarse N - N -bimodule, so that $N \subset M$ satisfies the malnormality condition.

We end with a result showing that the order of magnitude of the paving size obtained in Theorem 5.1 is optimal. More generally, we show that, for any MASA in any II_1 factor, the ε paving size is at least ε^{-2} , i.e., $\sup\{n(\varepsilon, x) \mid x \in M_{\text{sa}}\} \geq \varepsilon^{-2}$. The proof is very similar to [Casazza et al. 2007, Theorem 6], where it was shown that one needs at least ε^{-2} projections to ε pave self-adjoint unitary matrices.

Proposition 5.4. *Let M be a II_1 factor and $A \subset M$ a diffuse abelian von Neumann subalgebra. Let $\varepsilon > 0$ and $n < \varepsilon^{-2}$. There exists a self-adjoint unitary $x \in M$ with $E_A(x) = 0$ and*

$$\left\| \sum_{k=1}^n p_k x p_k \right\| \geq \left\| \sum_{k=1}^n p_k x p_k \right\|_2 > \varepsilon \tag{5-1}$$

for every decomposition of the identity $1 = p_1 + \dots + p_n$ with n projections $p_k \in A$.

So, if $A \subset M$ is a MASA in a II_1 factor, then the uniform L^2 paving size of $A^\omega \subset M^\omega$ is exactly equal to the smallest integer that is greater than or equal to ε^{-2} .

Proof. Fix $\varepsilon > 0$ and $n < \varepsilon^{-2}$. Take r large enough such that

$$\frac{r}{r-1} \frac{1}{n} - \frac{1}{r-1} > \varepsilon^2 \tag{5-2}$$

and such that there exists a conference matrix $C \in M_r(\mathbb{R})$ of size r , that is,

$$C_{ij} = \pm 1 \quad \text{if } i \neq j, \quad C_{ii} = 0 \quad \text{for all } i, \quad \text{and} \quad (r-1)^{-1/2} C \quad \text{is a self-adjoint unitary.}$$

Since A is diffuse, we can choose projections $e_1, \dots, e_r \in A$ with $1 = e_1 + \dots + e_r$ and $\tau(e_i) = 1/r$ for every i . Since M is a II_1 factor, we can choose partial isometries $v_1, \dots, v_r \in M$ such that $v_i v_i^* = e_1$ and $v_i^* v_i = e_i$ for all i . Define

$$x = \frac{1}{\sqrt{r-1}} \sum_{i,j=1}^r C_{ij} v_i^* v_j.$$

Note that x is a self-adjoint unitary. Since A is abelian, we have for all $i \neq j$ that

$$0 = e_i e_j E_A(v_i^* v_j) = e_i E_A(v_i^* v_j) e_j = E_A(e_i v_i^* v_j e_j) = E_A(v_i^* v_j).$$

Since $C_{ii} = 0$ for all i , we get that $E_A(x) = 0$.

Choose an arbitrary decomposition of the identity $1 = p_1 + \dots + p_n$ with n projections $p_k \in A$. We prove that (5-1) holds. First note that

$$\left\| \sum_{k=1}^n p_k x p_k \right\|_2^2 = \sum_{k=1}^n \|p_k x p_k\|_2^2 = \sum_{k=1}^n \tau(p_k x p_k x). \tag{5-3}$$

Since A is abelian, we can define the projections $p_{ik} = e_i p_k$. Writing $p_k = \sum_{i=1}^r p_{ik}$, we get for every $k \in \{1, \dots, n\}$ that

$$\begin{aligned} \tau(p_k x p_k x) &= \sum_{i,j=1}^r \tau(p_{ik} x p_{jk} x) = \sum_{i,j=1}^r \tau(p_{ik} x p_{jk} x e_i) \\ &= \frac{1}{r-1} \sum_{i,j=1}^r C_{ij}^2 \tau(p_{ik} v_i^* v_j p_{jk} v_j^* v_i) \\ &= \frac{1}{r-1} \left(\sum_{i,j=1}^r \tau(v_i p_{ik} v_i^* v_j p_{jk} v_j^*) - \sum_{i=1}^r \tau(v_i p_{ik} v_i^* v_i p_{ik} v_i^*) \right) \\ &= \frac{1}{r-1} (\tau(T_k^2) - \tau(p_k)), \quad \text{where } T_k = \sum_{i=1}^r v_i p_{ik} v_i^*. \end{aligned}$$

In combination with (5-3), it follows that

$$\left\| \sum_{k=1}^n p_k x p_k \right\|_2^2 = \frac{1}{r-1} \tau \left(\sum_{k=1}^n T_k^2 \right) - \frac{1}{r-1}. \tag{5-4}$$

We next observe that, as positive operators, we have

$$\sum_{k=1}^n T_k^2 \geq \frac{1}{n} \left(\sum_{k=1}^n T_k \right)^2. \tag{5-5}$$

Indeed, defining the elements $T, R \in M_{1,n}(\mathbb{C}) \otimes M$ given by

$$T = (T_1 \ T_2 \ \dots \ T_n) \quad \text{and} \quad R = (1 \ 1 \ \dots \ 1),$$

we get that

$$\left(\sum_{k=1}^n T_k \right)^2 = TR^*RT^* \leq \|R\|^2 TT^* = n \sum_{k=1}^n T_k^2.$$

So, (5-5) follows. By construction, we have that $\sum_{k=1}^n T_k = r e_1$. So, in combination with (5-4) and (5-2), we find that

$$\left\| \sum_{k=1}^n p_k x p_k \right\|_2^2 \geq \frac{1}{r-1} \frac{1}{n} \tau(r^2 e_1) - \frac{1}{r-1} = \frac{1}{r-1} \frac{r}{n} - \frac{1}{r-1} > \varepsilon^2.$$

Thus we have proved (5-1).

Now assume that $A \subset M$ is a MASA in the II_1 factor M . It follows that the uniform L^2 -paving size of $A^\omega \subset M^\omega$ is at least ε^{-2} . On the other hand, if n is an integer and $n \geq \varepsilon^{-2}$, it was proved in [Popa 2014, Section 3] that every element $x \in M^\omega$ can be (ε, n) L^2 -paved. \square

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