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On stability of discrete-time quantum filters

Pierre Rouchon*

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Fidelity is known to increase through a Kraus map: the fidelity between two density matrices is less than the fidelity between their images via a Kraus map. We prove here that, in average, the square of the fidelity is also increasing for a quantum filter: the square of the fidelity between the density matrix of the underlying Markov chain and the density matrix of its associated quantum filter is a super-martingale. Thus discrete-time quantum filters are stable processes and tend to forget their initial conditions.

1 Kraus maps and quantum Markov chains

Take the Hilbert space $S = \mathbb{C}^n$ of dimension $n > 0$ and consider a quantum channel described by the Kraus map (see [3], chapter 4)

$$\mathcal{K}(\rho) = \sum_{\mu=1}^m M_{\mu} \rho M_{\mu}^{\dagger} \quad (1)$$

where

- ρ is the density matrix describing the input quantum state, $\mathcal{K}(\rho)$ being then the output quantum state; $\rho \in \mathbb{C}^{n \times n}$ is a density matrix, i.e., an Hermitian matrix semi-positive definite and of trace one;
- for each $\mu \in \{1, \dots, m\}$, $M_{\mu} \in \mathbb{C}^{n \times n} / \{0\}$, and $\sum_{\mu} M_{\mu}^{\dagger} M_{\mu} = I$.

To this quantum channel is associated the following discrete-time Markov chain:

$$\rho_{k+1} = \mathcal{M}_{\mu_k}(\rho_k) \quad (2)$$

where

- ρ_k is the quantum state at sampling time t_k and k the sampling index ($t_k < t_{k+1}$).
- $\mu_k \in \{1, \dots, m\}$ is a random variable; $\mu_k = \mu$ with probability $p_{\mu}(\rho_k) = \text{Tr}(M_{\mu} \rho_k M_{\mu}^{\dagger})$.

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- $\mathcal{M}_\mu(\rho) = \frac{1}{\text{Tr}(M_\mu \rho M_\mu^\dagger)} M_\mu \rho M_\mu^\dagger = \frac{1}{p_\mu(\rho)} M_\mu \rho M_\mu^\dagger$.

Kraus maps are contractions for the trace distance, i.e., nuclear distance (see [3], theorem 9.2, page 406): for all density matrices σ, ρ , one has

$$\text{Tr} (|\mathcal{K}(\sigma) - \mathcal{K}(\rho)|) \leq \text{Tr} (|\sigma - \rho|)$$

where, for any Hermitian matrix A with spectrum $\{\lambda_l\}_{l \in \{1, \dots, n\}}$, $\text{Tr} (|A|) = \sum_{l=1}^n |\lambda_l|$. The Kraus map tends also to increase fidelity F (see [3], theorem 9.6, page 414): for all density matrices ρ and σ , one has

$$\text{Tr} \left(\sqrt{\sqrt{\mathcal{K}(\sigma)} \mathcal{K}(\rho) \sqrt{\mathcal{K}(\sigma)}} \right) = F(\mathcal{K}(\sigma), \mathcal{K}(\rho)) \geq F(\sigma, \rho) = \text{Tr} \left(\sqrt{\sqrt{\sigma} \rho \sqrt{\sigma}} \right) \quad (3)$$

where, for any Hermitian semi-positive matrix $A = U \Lambda U^\dagger$, U unitary matrix and $\Lambda = \text{diag}\{\lambda_l\}_{l \in \{1, \dots, n\}}$, $\sqrt{A} = U \sqrt{\Lambda} U^\dagger$ with $\sqrt{\Lambda} = \text{diag}\{\sqrt{\lambda_l}\}_{l \in \{1, \dots, n\}}$.

The conditional expectation of ρ_{k+1} knowing ρ_k is given by the Kraus map:

$$\mathbb{E}(\rho_{k+1}/\rho_k) = \mathcal{K}(\rho_k).$$

This result from the trivial identity $\sum_{\mu=1}^m \text{Tr} (M_\mu \rho M_\mu^\dagger) \frac{M_\mu \rho M_\mu^\dagger}{\text{Tr}(M_\mu \rho M_\mu^\dagger)} = \mathcal{K}(\rho)$. In section 2, we show during the proof of theorem (1) the following inequality

$$\sum_{\mu=1}^m \text{Tr} (M_\mu \rho M_\mu^\dagger) F^2 \left(\frac{M_\mu \sigma M_\mu^\dagger}{\text{Tr}(M_\mu \sigma M_\mu^\dagger)}, \frac{M_\mu \rho M_\mu^\dagger}{\text{Tr}(M_\mu \rho M_\mu^\dagger)} \right) \geq F^2(\sigma, \rho) \quad (4)$$

for any density matrices ρ and σ . The left-hand side is related to a conditional expectation. Inequality (4), attached to the probabilistic mapping (2), can be seen as the stochastic counter-part of inequality (3) attached to the deterministic mapping (1). When for some μ , $\text{Tr} (M_\mu \sigma M_\mu^\dagger) = 0$ with $\text{Tr} (M_\mu \rho M_\mu^\dagger) > 0$, one term in the sum at the left-hand side of (4) is not defined. This is not problematic, since in this case, if we replace $\frac{M_\mu \sigma M_\mu^\dagger}{\text{Tr}(M_\mu \sigma M_\mu^\dagger)}$ by $\frac{M_\mu \xi M_\mu^\dagger}{\text{Tr}(M_\mu \xi M_\mu^\dagger)}$ where ξ is any density matrix such that $\text{Tr} (M_\mu \xi M_\mu^\dagger) > 0$, this term is then well defined (in a multi-valued way) and inequality (4) remains satisfied for any such ξ .

During the proof of theorem (8), we extend this inequality to any partition of $\{1, \dots, m\}$ into $p \geq 1$ sub-sets \mathcal{P}_ν :

$$\sum_{\nu=1}^p \text{Tr} \left(\sum_{\mu \in \mathcal{P}_\nu} M_\mu \rho M_\mu^\dagger \right) F^2 \left(\frac{\sum_{\mu \in \mathcal{P}_\nu} M_\mu \sigma M_\mu^\dagger}{\text{Tr}(\sum_{\mu \in \mathcal{P}_\nu} M_\mu \sigma M_\mu^\dagger)}, \frac{\sum_{\mu \in \mathcal{P}_\nu} M_\mu \rho M_\mu^\dagger}{\text{Tr}(\sum_{\mu \in \mathcal{P}_\nu} M_\mu \rho M_\mu^\dagger)} \right) \geq F^2(\sigma, \rho) \quad (5)$$

2 The standard case.

Take a realization of the Markov chain associated to the Kraus map \mathcal{K} . Assume that we detect, for each k , the jump μ_k but that we do not know the initial state ρ_0 . The objective is to propose at sampling k , an estimation $\hat{\rho}_k$ of ρ_k based on the past detections μ_0, \dots, μ_{k-1} . The simplest method consists in starting from an initial estimation $\hat{\rho}_0$ and at each sampling step to jump according to the detection. This leads to the following estimation scheme known as a *quantum filter*:

$$\hat{\rho}_{k+1} = \mathcal{M}_{\mu_k}(\hat{\rho}_k) \quad (6)$$

with $p_\mu(\rho_k) = \text{Tr}(M_\mu \rho_k M_\mu)$ as probability of $\mu_k = \mu$. Notice that when $\text{Tr}(M_{\mu_k} \hat{\rho}_k M_{\mu_k}) = 0$, $\mathcal{M}_{\mu_k}(\hat{\rho}_k)$ is not defined and should be replaced by $\mathcal{M}_{\mu_k}(\xi)$ where ξ is any density matrix such that $\text{Tr}(M_{\mu_k} \xi M_{\mu_k}) > 0$ (take, e.g., $\xi = \frac{1}{n} I_d$). The theorem here below is a first step to investigate the convergence of $\hat{\rho}_k$ towards ρ_k as k increases.

Theorem 1. *Consider the Markov chain of state $(\rho_k, \hat{\rho}_k)$ satisfying (2) and (6). Then $F^2(\hat{\rho}_k, \rho_k)$ is a super-martingale: $\mathbb{E}(F^2(\hat{\rho}_{k+1}, \rho_{k+1}) / (\hat{\rho}_k, \rho_k)) \geq F^2(\hat{\rho}_k, \rho_k)$.*

When $\hat{\rho}_k$ or ρ_k are pure states, $\hat{\rho}_{k+1}$ or ρ_{k+1} remain also a pure states. Then, $F^2(\hat{\rho}_k, \rho_k) = \text{Tr}(\hat{\rho}_k \rho_k)$ and $F^2(\hat{\rho}_{k+1}, \rho_{k+1}) = \text{Tr}(\hat{\rho}_{k+1}, \rho_{k+1})$. In this case, theorem 1 has been proved in [2] using Cauchy-Schwartz inequalities for $m = 2$. The proof proposed here below deals with the general case when both ρ_k and $\hat{\rho}_k$ can be mixed states. It relies on arguments similar to those used for the proof of theorem 9.6 in [3].

Proof. ρ and $\hat{\rho}$ are associated to the Hilbert space $S = \mathbb{C}^n$: ρ and $\hat{\rho}$ are operators from S to S . Take a copy $Q = \mathbb{C}^n$ of S and consider the composite system living on $S \otimes Q \equiv \mathbb{C}^{n^2}$. Then $\hat{\rho}$ and ρ correspond to partial traces versus Q of projectors $|\hat{\psi}\rangle\langle\hat{\psi}|$ and $|\psi\rangle\langle\psi|$ associated to pure states $|\hat{\psi}\rangle$ and $|\psi\rangle \in S \otimes Q$:

$$\hat{\rho} = \text{Tr}_Q(|\hat{\psi}\rangle\langle\hat{\psi}|), \quad \rho = \text{Tr}_Q(|\psi\rangle\langle\psi|)$$

$|\hat{\psi}\rangle$ and $|\psi\rangle$ are called purifications of $\hat{\rho}$ and ρ . They are not unique but one can always choose them such that $F(\hat{\rho}, \rho) = |\langle\hat{\psi}|\psi\rangle|$ (Uhlmann's theorem).

Denote by $|\hat{\psi}_k\rangle$ and $|\psi_k\rangle$ such purifications of $\hat{\rho}_k$ and ρ_k satisfying $F(\hat{\rho}_k, \rho_k) = |\langle\hat{\psi}_k|\psi_k\rangle|$. We have

$$\mathbb{E}(F^2(\hat{\rho}_{k+1}, \rho_{k+1}) / (\hat{\rho}_k, \rho_k)) = \sum_{\mu=1}^m p_\mu(\rho_k) F^2(\mathcal{M}_\mu(\hat{\rho}_k), \mathcal{M}_\mu(\rho_k)).$$

The matrices $\mathcal{M}_\mu(\hat{\rho}_k)$ and $\mathcal{M}_\mu(\rho_k)$ are also density matrices. Take the space $S \otimes Q \otimes E$ where E is the Hilbert space of the environment appearing in the system-environment model of the Kraus map (1). This model is recalled in appendix A. It introduced an unitary transformation U on $S \otimes E$. This unitary transformation can be extended to $S \otimes Q \otimes E \equiv S \otimes E \otimes Q$ by setting $V = U \otimes I$ (I is identity on Q). Then

$$M_\mu(\rho_k) = \text{Tr}_{Q \otimes E}(P_\mu V(|\psi_k\rangle\langle\psi_k| \otimes |e_0\rangle\langle e_0|) V^\dagger P_\mu).$$

Set $|\phi_k\rangle = |\psi_k\rangle \otimes |e_0\rangle \in S \otimes Q \otimes E$ and $|\chi_k\rangle = V|\phi_k\rangle$. Using $P_\mu^2 = P_\mu$, we have

$$p_\mu(\rho_k) = \text{Tr}(M_\mu(\rho_k)) = \langle \phi_k | V^\dagger P_\mu V | \phi_k \rangle = \|P_\mu |\chi_k\rangle\|^2$$

For each μ , the state $|\chi_{k\mu}\rangle = \frac{1}{\sqrt{p_\mu(\rho_k)}} P_\mu |\chi_k\rangle$ is a purification of $\mathcal{M}_\mu(\rho_k)$:

$$\mathcal{M}_\mu(\rho_k) = \text{Tr}_{Q \otimes E} (|\chi_{k\mu}\rangle \langle \chi_{k\mu}|).$$

Similarly set $|\hat{\phi}_k\rangle = |\hat{\psi}_k\rangle \otimes |e_0\rangle$ and $|\hat{\chi}_k\rangle = V|\hat{\phi}_k\rangle$. For each μ , $|\hat{\chi}_{k\mu}\rangle = \frac{1}{\sqrt{p_\mu(\hat{\rho}_k)}} P_\mu |\hat{\chi}_k\rangle$ is also a purification of $\mathcal{M}_\mu(\hat{\rho}_k)$. By Uhlmann's theorem,

$$F^2(\mathcal{M}_\mu(\hat{\rho}_k), \mathcal{M}_\mu(\rho_k)) \geq |\langle \hat{\chi}_{k\mu} | \chi_{k\mu} \rangle|^2.$$

Thus we have

$$\mathbb{E} (F^2(\hat{\rho}_{k+1}, \rho_{k+1}) / (F^2(\hat{\rho}_k, \rho_k))) \geq \sum_{\mu=1}^m p_\mu(\rho_k) |\langle \hat{\chi}_{k\mu} | \chi_{k\mu} \rangle|^2.$$

Since V is unitary,

$$|\langle \hat{\chi}_k | \chi_k \rangle|^2 = |\langle \hat{\phi}_k | \phi_k \rangle|^2 = |\langle \hat{\psi}_k | \psi_k \rangle|^2 = F^2(\hat{\rho}_k, \rho_k).$$

Let us show that $\sum_{\mu=1}^m p_\mu(\rho_k) |\langle \hat{\chi}_{k\mu} | \chi_{k\mu} \rangle|^2 \geq |\langle \hat{\chi}_k | \chi_k \rangle|^2$. We have

$$p_\mu(\rho_k) |\langle \hat{\chi}_{k\mu} | \chi_{k\mu} \rangle|^2 = |\langle \hat{\chi}_{k\mu} | P_\mu \chi_k \rangle|^2 = |\langle \hat{\chi}_{k\mu} | \chi_k \rangle|^2,$$

thus it is enough to prove that $\sum_{\mu=1}^m |\langle \hat{\chi}_{k\mu} | \chi_k \rangle|^2 \geq |\langle \hat{\chi}_k | \chi_k \rangle|^2$. Denote by $\hat{R} \subset S \otimes Q \otimes E$ the vector space spanned by the ortho-normal basis $(|\hat{\chi}_{k\mu}\rangle)_{\mu \in \{1, \dots, m\}}$ and by \hat{P} the projector on \hat{R} . Since

$$|\hat{\chi}_k\rangle = \sum_{\mu=1}^m P_\mu |\hat{\chi}_k\rangle = \sum_{\mu=1}^m \sqrt{p_\mu(\hat{\rho}_k)} |\hat{\chi}_{k\mu}\rangle$$

$|\hat{\chi}_k\rangle$ belongs to \hat{R} and thus $|\langle \hat{\chi}_k | \chi_k \rangle|^2 = |\langle \hat{\chi}_k | \hat{P} |\chi_k\rangle|^2$. We conclude by Cauchy-Schwartz inequality

$$|\langle \hat{\chi}_k | \chi_k \rangle|^2 = |\langle \hat{\chi}_k | \hat{P} |\chi_k\rangle|^2 \leq \|\hat{\chi}_k\|^2 \|\hat{P} |\chi_k\rangle\|^2 = \|\hat{P} |\chi_k\rangle\|^2 = \sum_{\mu=1}^m |\langle \hat{\chi}_{k\mu} | \chi_k \rangle|^2.$$

□

3 The aggregated case.

Let us consider another Markov chain attached to the same Kraus map (1) and associated to a partition of $\{1, \dots, m\}$ into $p \geq 1$ sub-sets \mathcal{P}_ν (aggregation of several quantum jumps via "partial Kraus maps"):

$$\rho_{k+1} = \frac{1}{\text{Tr}(\sum_{\mu \in \mathcal{P}_{\nu_k}} M_\mu \rho_k M_\mu^\dagger)} \left(\sum_{\mu \in \mathcal{P}_{\nu_k}} M_\mu \rho_k M_\mu^\dagger \right) \quad (7)$$

where $\nu_k = \nu$ with probability $\text{Tr} \left(\sum_{\mu \in \mathcal{P}_\nu} M_\mu \rho_k M_\mu^\dagger \right)$. Consider the associated quantum filter

$$\hat{\rho}_{k+1} = \frac{1}{\text{Tr} \left(\sum_{\mu \in \mathcal{P}_{\nu_k}} M_\mu \hat{\rho}_k M_\mu^\dagger \right)} \left(\sum_{\mu \in \mathcal{P}_{\nu_k}} M_\mu \hat{\rho}_k M_\mu^\dagger \right) \quad (8)$$

where the jump index ν_k coincides with the jump index ν_k in (7). Then we have the following theorem.

Theorem 2. *Consider the Markov chain of state $(\rho_k, \hat{\rho}_k)$ satisfying (7) and (8). Then $F^2(\hat{\rho}_k, \rho_k)$ is a super-martingale: $\mathbb{E} (F^2(\hat{\rho}_{k+1}, \rho_{k+1}) / (\hat{\rho}_k, \rho_k)) \geq F^2(\hat{\rho}_k, \rho_k)$.*

Proof. It is similar to the proof of theorem 1. We will just point out here the main changes using the same notations. We start from

$$\mathbb{E} (F^2(\hat{\rho}_{k+1}, \rho_{k+1}) / (\hat{\rho}_k, \rho_k)) = \sum_{\nu=1}^p \tilde{p}_\nu(\rho_k) F^2(\tilde{\mathcal{M}}_\nu(\hat{\rho}_k), \tilde{\mathcal{M}}_\nu(\rho_k)).$$

where we have set

$$\tilde{p}_\nu(\rho) = \text{Tr} \left(\sum_{\mu \in \mathcal{P}_\nu} M_\mu \rho M_\mu^\dagger \right), \quad \tilde{\mathcal{M}}_\nu(\rho) = \frac{1}{\tilde{p}_\nu(\rho)} \left(\sum_{\mu \in \mathcal{P}_\nu} M_\mu \rho M_\mu^\dagger \right).$$

With \tilde{P}_ν the orthogonal projector on $S \otimes Q \otimes \text{span}\{|\mu\rangle, \mu \in \mathcal{P}_\nu\}$ and $\tilde{M}_\nu(\rho) = \sum_{\mu \in \mathcal{P}_\nu} M_\mu \rho M_\mu^\dagger$, we have

$$\tilde{M}_\nu(\rho_k) = \text{Tr}_{Q \otimes E} \left(\tilde{P}_\nu V (|\psi_k\rangle\langle\psi_k| \otimes |e_0\rangle\langle e_0|) V^\dagger \tilde{P}_\nu \right)$$

and

$$\tilde{p}_\nu(\rho_k) = \text{Tr} \left(\tilde{M}_\nu(\rho_k) \right) = \langle \phi_k | V^\dagger \tilde{P}_\nu V | \phi_k \rangle = \|\tilde{P}_\nu |\chi_k\rangle\|^2$$

For each ν , the state $|\tilde{\chi}_{k\nu}\rangle = \frac{1}{\sqrt{\tilde{p}_\nu(\rho_k)}} \tilde{P}_\nu |\chi_k\rangle$ is a purification of $\tilde{\mathcal{M}}_\nu(\rho_k)$:

$$\tilde{\mathcal{M}}_\nu(\rho_k) = \text{Tr}_{Q \otimes E} (|\tilde{\chi}_{k\nu}\rangle\langle\tilde{\chi}_{k\nu}|).$$

Similarly $|\hat{\chi}_{k\nu}\rangle = \frac{1}{\sqrt{\tilde{p}_\nu(\hat{\rho}_k)}} \tilde{P}_\nu |\hat{\chi}_k\rangle$ is also a purification of $\tilde{\mathcal{M}}_\nu(\hat{\rho}_k)$. By Uhlmann's theorem,

$$F^2(\tilde{\mathcal{M}}_\nu(\hat{\rho}_k), \tilde{\mathcal{M}}_\nu(\rho_k)) \geq |\langle \hat{\chi}_{k\nu} | \tilde{\chi}_{k\nu} \rangle|^2.$$

Thus we have

$$\mathbb{E} (F^2(\hat{\rho}_{k+1}, \rho_{k+1}) / (\hat{\rho}_k, \rho_k)) \geq \sum_{\nu=1}^p \tilde{p}_\nu(\rho_k) |\langle \hat{\chi}_{k\nu} | \tilde{\chi}_{k\nu} \rangle|^2.$$

Let us show that $\sum_{\nu=1}^p \tilde{p}_\nu(\rho_k) |\langle \hat{\chi}_{k\nu} | \tilde{\chi}_{k\nu} \rangle|^2 \geq |\langle \hat{\chi}_k | \chi_k \rangle|^2 = F^2(\hat{\rho}_k, \rho_k)$. We have

$$\tilde{p}_\nu(\rho_k) |\langle \hat{\chi}_{k\nu} | \tilde{\chi}_{k\nu} \rangle|^2 = |\langle \hat{\chi}_{k\nu} | \tilde{P}_\nu \chi_k \rangle|^2 = |\langle \hat{\chi}_{k\nu} | \chi_k \rangle|^2,$$

thus it is enough to prove that $\sum_{\nu=1}^p |\langle \hat{\chi}_{k\nu} | \chi_k \rangle|^2 \geq |\langle \hat{\chi}_k | \chi_k \rangle|^2$. Denote by $\hat{R} \subset S \otimes Q \otimes E$ the vector space spanned by the ortho-normal basis $(|\hat{\chi}_{k\nu}\rangle)_{\nu \in \{1, \dots, p\}}$ and by \hat{P} the projector on \hat{R} . Since

$$|\hat{\chi}_k\rangle = \sum_{\nu=1}^p \tilde{P}_\nu |\hat{\chi}_{k\nu}\rangle = \sum_{\nu=1}^p \sqrt{\tilde{p}_\nu(\hat{\rho}_k)} |\hat{\chi}_{k\nu}\rangle$$

$|\hat{\chi}_k\rangle$ belongs to \hat{R} and thus $|\langle \hat{\chi}_k | \chi_k \rangle|^2 = |\langle \hat{\chi}_k | \hat{P} | \chi_k \rangle|^2$. We conclude by Cauchy-Schwartz inequality

$$|\langle \hat{\chi}_k | \chi_k \rangle|^2 = |\langle \hat{\chi}_k | \hat{P} | \chi_k \rangle|^2 \leq \|\hat{\chi}_k\|^2 \|\hat{P} | \chi_k \rangle\|^2 = \|\hat{P} | \chi_k \rangle\|^2 = \sum_{\nu=1}^p |\langle \hat{\chi}_{k\nu} | \chi_k \rangle|^2.$$

□

4 Concluding remarks

Theorems 1 and 2 are still valid if the Kraus operators M_μ depend on k . In particular, $F(\hat{\rho}_k, \rho_k)$ remains a super-martingale even if the Kraus operators depend on $\hat{\rho}_k$, i.e., in case of feedback.

When σ and ρ are pure states (projectors of rank one), $D(\sigma, \rho) = \sqrt{1 - F^2(\sigma, \rho)}$. Consequently inequality (4) yields to

$$\sum_{\mu=1}^m \text{Tr}(M_\mu \rho M_\mu^\dagger) D\left(\frac{M_\mu \sigma M_\mu^\dagger}{\text{Tr}(M_\mu \sigma M_\mu^\dagger)}, \frac{M_\mu \rho M_\mu^\dagger}{\text{Tr}(M_\mu \rho M_\mu^\dagger)}\right) \leq D(\sigma, \rho)$$

for any pure states σ and ρ (use the fact that $[0, x] \ni x \mapsto \sqrt{1-x}$ is decreasing and concave). We conjecture that such inequality hold also true for any mixed states and that $D(\hat{\rho}_k, \rho_k) = \text{Tr}(|\hat{\rho}_k - \rho_k|)$ is a sub-martingale.

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A System-environment model

The quantum channel associated to the Kraus map (1) or the Markov chain (2) admits a system-environment model (see [1], chapter 4 entitled "The environment is watching"). Take the Hilbert space $E = \mathbb{C}^m$ associated to the environment and the composite system living on $S \otimes E$. Take a pure state $|\phi_k\rangle \in S$ and its density matrix $\rho_k = |\phi_k\rangle\langle\phi_k|$. Assume that before detection μ_k at step k , the composite system admits the pure state $|\phi_k\rangle \otimes |e_0\rangle$ where $|e_0\rangle$ is an environment pure state. Take m states $|\mu\rangle$ forming an orthogonal base of E . Then exists a unitary transformation U (not unique) of $S \otimes E$ such that, for all $|\phi\rangle \in S$,

$$U(|\phi\rangle \otimes |e_0\rangle) = \sum_{\mu=1}^m (M_\mu|\phi\rangle) \otimes |\mu\rangle.$$

This is a direct consequence of $\sum_{\mu=1}^m M_\mu^\dagger M_\mu = I$. For each μ , denote by P_μ the orthogonal projector onto the subspace $S \otimes (\mathbb{C}|\mu\rangle)$. Then $P_\mu U(|\phi\rangle \otimes |e_0\rangle) = (M_\mu|\phi\rangle) \otimes |\mu\rangle$ and $\sum_\mu P_\mu = I$. We can then verify that for any density matrix ρ associated to a state in R ,

$$P_\mu U(\rho \otimes |e_0\rangle\langle e_0|) U^\dagger P_\mu = M_\mu \rho M_\mu^\dagger \otimes |\mu\rangle\langle\mu|$$

and thus

$$\text{Tr}_E(P_\mu U(\rho \otimes |e_0\rangle\langle e_0|) U^\dagger P_\mu) = M_\mu \rho M_\mu^\dagger.$$