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Quasi-compactness and mean ergodicity for Markov kernels acting on weighted supremum normed spaces

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Abstract. Let P be a Markov kernel on a measurable space E with countably generated σ-algebra, let $w : E \to [1, +\infty[$ such that $Pw \le Cw$ with $C \ge 0$, and let $\mathcal{B}_w$ be the space of measurable functions on E satisfying $\|f\|_w = \sup\{w(x)^{-1}|f(x)|,\ x \in E\} < +\infty$. We prove that P is quasi-compact on $(\mathcal{B}_w, \|\cdot\|_w)$ if and only if, for all $f \in \mathcal{B}_w$, $(\frac{1}{n}\sum_{k=1}^n P^k f)_n$ contains a subsequence converging in $\mathcal{B}_w$ to $\Pi f = \sum_{i=1}^d \mu_i(f) v_i$, where the v_i's are non-negative bounded measurable functions on E and the μ_i's are probability distributions on E. In particular, when the space of P-invariant functions in $\mathcal{B}_w$ is finite-dimensional, uniform ergodicity is equivalent to mean ergodicity.

Résumé. Soit P un noyau markovien sur un espace mesurable E muni d'une tribu à base dénombrable, soit $w : E \to [1, +\infty[$ tel que $Pw \le Cw$, avec $C \ge 0$, et soit $\mathcal{B}_w$ l'espace des fonctions f mesurables de E dans $\mathbb{C}$ telles que $\|f\|_w = \sup\{w(x)^{-1}|f(x)|,\ x \in E\} < +\infty$. Nous démontrons que P est quasi-compact sur $(\mathcal{B}_w, \|\cdot\|_w)$ si et seulement si, pour tout $f \in \mathcal{B}_w$, $(\frac{1}{n}\sum_{k=1}^n P^k f)_n$ contient une sous-suite convergeant dans $\mathcal{B}_w$ vers $\Pi f = \sum_{i=1}^d \mu_i(f) v_i$, où v_i est une fonction mesurable positive bornée sur E et μ_i une probabilité sur E. En particulier, quand le sous-espace de $\mathcal{B}_w$ constitué des fonctions P-invariantes est de dimension finie, la convergence uniforme des moyennes est équivalente à la convergence ponctuelle.

MSC: 37A30; 60J10

Keywords: Markov kernel; Quasi-compactness; Mean ergodicity; Geometrical ergodicity

1. Introduction

Let $(E, \mathcal{E})$ be a measurable space with countably generated σ-algebra, let $(\tilde{\mathcal{B}}, \|\cdot\|)$ denote the space of complex-valued bounded measurable functions on E, equipped with the supremum norm, and let P be a Markov kernel on $(E, \mathcal{E})$. Under some irreducibility conditions, P is quasi-compact on $\tilde{\mathcal{B}}$ if and only if P is mean ergodic with one-dimensional limit projection defined by the unique P-invariant distribution. This result was proved in [1] under the Harris condition (see also [11]), and in [8] under the ergodicity condition.[1] See also [6].

Now let $w : E \to [1, +\infty[$, and let $(\mathcal{B}_w, \|\cdot\|_w)$ denote the Banach space of complex-valued measurable functions on E satisfying $\|f\|_w := \sup\{w(x)^{-1}|f(x)|, x \in E\} < +\infty$. Assuming $Pw \le Cw$, with $C \in \mathbb{R}_+^*$, P acts continuously on $\mathcal{B}_w$. This work extends to $\mathcal{B}_w$ the equivalence between mean ergodicity with finite rank limit projection and quasi-compactness.

[1] The equivalence between mean ergodicity and quasi-compactness is not mentioned in [1], but it is an easy consequence of Theorem II.2 in [1]. In [8] $\mathcal{E}$ is not supposed to be countably generated.

Theorem 1. *P is quasi-compact on $\mathcal{B}_w$ if and only if there exist $d \in \mathbb{N}^*$, linearly independent non-negative functions $v_1, \ldots, v_d$ in $\tilde{\mathcal{B}}$, and P-invariant distributions $\mu_1, \ldots, \mu_d$ on E satisfying $\mu_i(w) < +\infty$ such that, for all $f \in \mathcal{B}_w$, the sequence $(\frac{1}{n}\sum_{k=1}^n P^k f)_n$ contains a subsequence converging in $\mathcal{B}_w$ to $\sum_{i=1}^d \mu_i(f)v_i$.*

Observe that the naive idea which consists in applying the similarity transformation $\tilde{P} : f \mapsto w^{-1}P(wf)$ in order to deduce the theorem from [1,8] does not work because $\tilde{P}$ is not Markovian when $\|Pw\|_w > 1$ (i.e. when w is not sub-invariant). The proof of Theorem 1 is actually based on a recent work of Hennion [3], which gives criteria for quasi-compactness of kernels acting on $\mathcal{B}_w$, on spectral theory [2], and on positive operator theory [12,13]. As in [3], the above theorem does not require any irreducibility or aperiodicity conditions; in this sense, when applied with $w = 1_E$, it improves [1,8]. This theorem shows too that a quasi-compact Markov kernel on $\mathcal{B}_w$ is necessarily power-bounded. This fact was already proved in [4] (Section IV.3), together with the equivalence between quasi-compactness and uniform ergodicity, which also follows from [9].

The above theorem does not hold when $\mathcal{B}_w$ is replaced with continuous function spaces. For instance, if E is a compact metric space and P is uniquely ergodic on the space $\mathcal{C}(E)$ of all complex-valued continuous functions on E, then P is mean ergodic [7], but in general P is not quasi-compact on $\mathcal{C}(E)$ (consider irrational rotations of the circle).[2]

We shall present in Section 3 (Corollary 1) a direct application to w-geometrically ergodic Markov chains [10] whose transition probability is, by definition, quasi-compact on $\mathcal{B}_w$, with $\lambda = 1$ as a simple eigenvalue and the unique peripheral eigenvalue. Many examples of such Markov chains, with unbounded functions w, are presented in [10].

A simple example is provided by the linear model $X_n = \alpha X_{n-1} + \varepsilon_n$, with $\alpha \in]-1, 1[$, where $(\varepsilon_n)_{n\geq 1}$ is an i.i.d. sequence of real-valued random variables, independent of X_0, such that $m = \mathbb{E}[|\varepsilon_1|] < +\infty$. In this case the state space is $E = \mathbb{R}$ with its Lebesgue sets, and $P(x, A) = \mathbb{E}[1_A(\alpha x + \varepsilon_1)]$, which yields $Pf(x) = \mathbb{E}[f(\alpha x + \varepsilon_1)]$. Let $w(y) = 1 + |y|$ $(y \in \mathbb{R})$. Then, for any $x \in \mathbb{R}$, we have $Pw(x) = \mathbb{E}[w(\alpha x + \varepsilon_1)] \leq 1 + |\alpha||x| + m$, so $Pw \leq |\alpha|w + L$, with $L = 1 - |\alpha| + m$. From this inequality, called drift condition, one can deduce that, if ε_1 has an everywhere positive density, then $(X_n)_n$ is w-geometrically ergodic [10] (Section 15.5.2). Observe that w is not sub-invariant. Indeed, $Pw(0) = 1 + m > w(0)$, so $\|Pw\|_w > 1$. Obviously, this conclusion extends to any function $w(y) = a + b|y|$, with constants $a, b > 0$. Actually, in most of the examples of w-geometrically ergodic Markov chains, w is not sub-invariant when it is unbounded.

Finally we shall see in Corollary 2 that, in the special case of denumerable Markov chains, the above theorem enables us to obtain an elementary proof of the above mentioned well-known fact that geometric ergodicity is equivalent to some drift condition.

2. Proof of Theorem 1

Proof of $\Rightarrow$. Suppose P is quasi-compact on $\mathcal{B}_w$. It is proved in [4] (Section IV.3) that $(\frac{1}{n}\sum_{k=1}^n P^k)_n$ converges in the operator norm topology to a finite dimensional projection Π of the form: $\Pi f = \sum_{i=1}^d \phi_i(f) f_i$, where the f_i's are linearly independent functions in $\tilde{\mathcal{B}}$ and the ϕ_i's are bounded complex measures on E such that $|\phi_i|(w) < +\infty$, with $|\phi_i|$ the total variation of ϕ_i. It remains to prove that one can choose f_i and ϕ_i such that $f_i \geq 0$ and ϕ_i is a probability measure on E. Notice that $\Pi(\mathcal{B}_w) \subset \tilde{\mathcal{B}}$, $\Pi \geq 0$ and $\Pi 1_E = 1_E$.

Let $\mathcal{B}_{\mathbb{R}}$ be the subspace of $\mathcal{B}_w$ composed of real-valued functions. Then $\Pi(\mathcal{B}_{\mathbb{R}})$ is a Banach lattice which is isomorphic to $\mathbb{R}^d$ with the preservation of the order relation [13]. Consequently there exist non-negative functions $g_1, \ldots, g_d$ in $\Pi(\mathcal{B}_w)$ and positive linear form $e_1^*, \ldots, e_d^*$ on $\Pi(\mathcal{B}_w)$ such that $g = \sum_{i=1}^d e_i^*(g)g_i$ for all $g \in \Pi(\mathcal{B}_w)$. Let $\psi_j = e_j^* \circ \Pi$. The ψ_j's are positive continuous linear forms on $\mathcal{B}_w$, and $\psi_j = \sum_{i=1}^d e_j^*(f_i)\phi_i$. Thus the ψ_j's are positive bounded measures on E such that $\psi_j(w) < +\infty$. Set $\mu_j = \frac{1}{\psi_j(E)}\psi_j$ and $v_j = \psi_j(E)g_j$. Then $\Pi f = \sum_{i=1}^d \psi_i(f)g_i = \sum_{i=1}^d \mu_i(f)v_i$, and the μ_i's are P-invariant (use $\Pi P = \Pi$). □

[2] Also consider $E = [0, 1]$ and $Pf(x) = \frac{1}{2}[f(\frac{x}{2}) + f(\frac{x+1}{2})]$. P is quasi-compact on the space of Lipschitz functions on [0, 1], so P is mean ergodic on the space of continuous functions on [0, 1], but is not quasi-compact on this space: indeed, for $|z| < 1$, $f_z = \sum_{n\geq 1} z^{n-1}\cos(2^n\pi\cdot)$ is a continuous function satisfying $Pf_z = zf_z$.

Proof of $\Leftarrow$. We shall denote by (ME) the mean ergodicity (subsequential) condition of Theorem 1. We set $\Pi f = \sum_{i=1}^{d} \mu_i(f) v_i$. If T is a continuous linear operator on $\mathcal{B}_w$, we denote by $\|T\|_w$ its operator norm, and by $r(T)$ its spectral radius. We denote by I the identity operator on $\mathcal{B}_w$. Given $a \in \mathbb{C}$ and $\rho > 0$, we set $D(a,\rho) = \{z\colon\ z \in \mathbb{C}, |z-a| \le \rho\}$.

Since $P1_E = 1_E$, we have $r(P) \ge 1$. Besides, there exists $n_k \nearrow +\infty$ such that $\sup_k \|n_k^{-1} \sum_{j=1}^{n_k} P^j w\|_w < +\infty$, thus $\sup_k n_k^{-1} \|P^{n_k} w\|_w < +\infty$. Since $\|P^n\|_w = \|P^n w\|_w$, one gets $r(P) = \lim_n \|P^n\|_w^{1/n} = 1$. In particular this yields $\sum_{n\ge 0} 2^{-(n+1)} \|P^n\|_w < +\infty$, so we can define the following bounded operator on $\mathcal{B}_w$, which is obviously Markovian:

$$Q = \sum_{n\ge 0} 2^{-(n+1)} P^n = (2I - P)^{-1}.$$

Proposition 1. *Q is quasi-compact on $\mathcal{B}_w$.*

Proof. Let $\nu = \frac{1}{d} \sum_{i=1}^{d} \mu_i$. Since the σ-algebra $\mathcal{E}$ is countably generated, there exist a non-negative measurable function α on $(E \times E, \mathcal{E} \otimes \mathcal{E})$ and a positive kernel S on E such that we have $Q(x, \mathrm{d}y) = \alpha(x,y)\,\mathrm{d}\nu(y) + S(x,\mathrm{d}y)$, with $S(x,\cdot) \perp \nu$, for each $x \in E$ [11]. For $p \in \mathbb{N}^*$, set $\alpha_p = \min\{\alpha, p\}$, and

$$T_p(x,\mathrm{d}y) = \alpha_p(x,y)\,\mathrm{d}\nu(y), \qquad S_p(x,\mathrm{d}y) = Q(x,\mathrm{d}y) - T_p(x,\mathrm{d}y).$$

If $f \in \mathcal{B}_w$, then $|T_p f| \le \|f\|_w T_p w \le p\nu(w)\|f\|_w$, so $T_p(\mathcal{B}_w) \subset \tilde{\mathcal{B}}$. Besides T_p acts continuously on $\mathcal{B}_w$, and so is S_p. In order to apply [3], observe that, for each $p \in \mathbb{N}^*$, the functions $\alpha_p^{(w)}(x,\cdot) = w(x)^{-1}\alpha_p(x,\cdot)w(\cdot)$, $x \in E$, are uniformly ν-integrable (use $\alpha_p^{(w)}(x,y) \le pw(y)$, $\nu(w) < +\infty$ and Lebesgue's theorem).

Finally, since $Q = \phi(P)$ with $\phi(z) = \sum_{n\ge 0} 2^{-(n+1)} z^n$ and ϕ is analytic on $D(0,\frac{3}{2})$, the spectral mapping theorem [2] yields $r(Q) = \phi(r(P)) = \phi(1) = 1$. Proposition 1 then follows from [3] and [4] (Section IV) via the following lemma. □

Lemma 1. *There exists $p \ge 1$ such that $r(S_p) < 1$.*

Proof. Suppose that $r(S_p) = 1$ for all $p \ge 1$. Since $S_p \ge 0$, there exists a positive continuous linear form, η_p, on $\mathcal{B}_w$ such that $\eta_p = \eta_p \circ S_p$ and $\eta_p(w) = 1$, see [12], p. 267. Let $\tilde{P}, \tilde{Q}, \tilde{T}_p, \tilde{S}_p, \tilde{\eta}_p$ be the restriction to $\tilde{\mathcal{B}}$ of P, Q, T_p, S_p, η_p. Since $\eta_p = \eta_p \circ S_p \le \eta_p \circ Q$ and $(\eta_p \circ Q - \eta_p)(1_E) = 0$, we have $\tilde{\eta}_p = \tilde{\eta}_p \circ \tilde{Q}$, thus $\tilde{\eta}_p \circ \tilde{P} = \tilde{\eta}_p$. Moreover we have:

(a) $\tilde{\eta}_p \ne 0$. Indeed, if $\tilde{\eta}_p = 0$, then, from $\eta_p \circ Q = \eta_p \circ T_p + \eta_p \circ S_p$ and $T_p(\mathcal{B}_w) \subset \tilde{\mathcal{B}}$, one would get $\eta_p \circ Q = \eta_p \circ S_p = \eta_p$, thus $\eta_p \circ P = \eta_p$. Then, by (ME), $\eta_p = \sum_{i=1}^{d} \eta_p(v_i)\mu_i$ would be a positive measure on E such that $\eta_p(\tilde{\mathcal{B}}) = \{0\}$, so $\eta_p = 0$, which is impossible.

(b) $\forall f \in \tilde{\mathcal{B}}$, $\eta_p(f) = \sum_{i=1}^{d} \eta_p(v_i)\mu_i(f)$. This follows from $\tilde{\eta}_p \circ \tilde{P} = \tilde{\eta}_p$ and (ME).

Now, from (a) and (b), there exist $j \in \{1,\ldots,d\}$ and $p_k \nearrow +\infty$ such that we have $\eta_{p_k}(v_j) \ne 0$. Besides $\eta_{p_k}(v_j)\mu_j(T_{p_k}1_E) \le \eta_{p_k}(T_{p_k}1_E) = \eta_{p_k}(Q1_E - S_{p_k}1_E) = 0$, thus $\mu_j(T_{p_k}1_E) = 0$. When $k \to +\infty$, this gives $\iint \alpha(x,y)\,\mathrm{d}\nu(y)\,\mathrm{d}\mu_j(x) = 0$, hence $\int \alpha(x_0,y)\,\mathrm{d}\nu(y) = 0$ for a $x_0 \in E$. So $Q(x_0,\cdot) = S(x_0,\cdot) \perp \nu$: there exists $A \in \mathcal{E}$ such that $Q(x_0,A) = 0$ and $\nu(A) = 1$.

But: $Q(x_0,A) = 0 \ \Rightarrow\ \forall n \ge 1, P^n 1_A(x_0) = 0 \ \Rightarrow\ \sum_{i=1}^{d} \mu_i(A)v_i(x_0) = 0$ (by condition (ME)). While: $\nu(A) = \frac{1}{d}\sum_{i=1}^{d} \mu_i(A) = 1 \ \Rightarrow\ \mu_i(A) = 1, i = 1,\ldots,d$.

Thus $\sum_{i=1}^{d} v_i(x_0) = 0$: this is impossible because (ME) gives $1_E = \sum_{i=1}^{d} v_i$. □

We shall denote by $\sigma(Q)$ and $\sigma(P)$ the spectrum of Q and P when acting on $\mathcal{B}_w$.

Lemma 2. *We have $\sigma(Q) \setminus \{1\} \subset D(\frac{2}{3},\frac{1}{3}) \cap D(0, 1-\varepsilon)$ for a certain $\varepsilon \in]0,1[$.*

Proof. We have $Q = \phi(P)$ with $\phi(z) = \frac{1}{2-z}$, thus $\sigma(Q) = \phi(\sigma(P))$ [2]. Since $r(P) = 1$, we get $\sigma(Q) \subset \phi(D(0,1)) = D(\frac{2}{3}, \frac{1}{3})$. So $\lambda = 1$ is the unique peripheral spectral value of Q, and Lemma 2 then follows from Proposition 1. □

Lemma 3. $\lambda = 1$ *is a first order pole for* P, *with a corresponding finite-rank residue.*

Proof. Set $\psi(z) = 2 - \frac{1}{z}$, $z \in \mathbb{C}^*$. Lemma 2 yields $0 \notin \sigma(Q)$, so Q is invertible on $\mathcal{B}_w$, ψ is analytic on a neighborhood of $\sigma(Q)$, and $P = 2I - Q^{-1} = \psi(Q)$. Thus $\sigma(P) = \psi(\sigma(Q))$, and $\sigma(P) \setminus \{1\} = \psi(\sigma(Q) \setminus \{1\}) \subset \psi(D(\frac{2}{3}, \frac{1}{3})) \cap \psi(D(0, 1-\varepsilon)) = D(0,1) \cap D(2, \frac{1}{1-\varepsilon})^c$. Thus $\lambda = 1$ is an isolated point in $\sigma(P)$. Let A_P and A_Q be the residue of the resolvent functions of P and Q at $\lambda = 1$. Let χ be an analytic function on a neighborhood of $\sigma(P)$ such that $\chi(V_0) = \{0\}$ and $\chi(V_1) = \{1\}$, where V_0 and V_1 are disjoint neighborhoods of the sets $\sigma(P) \setminus \{1\}$ and $\{1\}$, respectively. We know that $A_P = \chi(P)$ [2], thus $A_P = \chi(\psi(Q))$. Besides $W_0 = \psi^{-1}(V_0)$ and $W_1 = \psi^{-1}(V_1)$ are disjoint neighborhoods of respectively $\sigma(Q) \setminus \{1\}$ and $\{1\}$, and $\chi \circ \psi$ is an analytic function on $W_0 \cup W_1$ such that $\chi \circ \psi(W_0) = \{0\}$, $\chi \circ \psi(W_1) = \{1\}$. Thus $A_Q = \chi \circ \psi(Q)$, so $A_P = A_Q$. Since the Markov kernel Q is quasi-compact on $\mathcal{B}_w$ (Proposition 1) and Q is power-bounded [4] (Theorem IV.3(i)), $\lambda = 1$ is a first order pole for Q, and $A_Q(\mathcal{B}_w) = \mathrm{Ker}(Q - I)$ is finite-dimensional by [2] (Theorem VIII.8.3 and Corollary VIII.8.4). By the definition of Q as a series, $Pf = f$ implies $Qf = f$ ($f \in \mathcal{B}_w$), and the converse holds by using $P = 2I - Q^{-1}$. Finally $A_P(\mathcal{B}_w) = A_Q(\mathcal{B}_w) = \mathrm{Ker}(Q - I) = \mathrm{Ker}(P - I)$ is finite-dimensional, so $\lambda = 1$ is a first order pole for P (use the arguments of [2], Theorem VII.4.5). □

Lemma 4. $\{\lambda \in \sigma(P), |\lambda| = 1\}$ *is composed of a finite number of first order poles.*

Proof. From Lemma 3 and a classical result concerning the peripheral spectrum of positive operators on Banach lattice [13] (Theorem 5.5, p. 331), the set of peripheral spectral values of P is composed of a finite number of poles for P. Using the Laurent expansions, Lemma 3 implies that they are first order poles. □

Lemma 5. *For any peripheral pole* λ *of* P, *we have* $\dim \mathrm{Ker}(P - \lambda I) \le \dim \mathrm{Ker}(P - I) < +\infty$.

Proof. We have $\dim \mathrm{Ker}(P - I) < +\infty$ by (ME). Let $\lambda_1 = 1, \lambda_2, \ldots, \lambda_m$ be the peripheral poles of P. The previous results show that $\mathcal{B}_w = \mathrm{Ker}(P - I) \oplus F \oplus H$, where $F = \bigoplus_{i=2}^m \mathrm{Ker}(P - \lambda_i I)$, and H is a P-invariant closed subspace of $\mathcal{B}_w$ such that $r(P_{|H}) < 1$, with $P_{|H}$ the restriction of P to H. Thus $(\frac{1}{n}\sum_{k=1}^n P^k)_n$ converges in the operator norm topology to the projection onto $\mathrm{Ker}(P - I)$. Then Lemma 5 follows from [9] (Theorem 2). □

The quasi-compactness of P on $\mathcal{B}_w$ follows from Lemmas 4 and 5. □

3. Applications to geometrically ergodic Markov chains

Let $(X_n)_{n\ge0}$ be a Markov chain with state space E and transition probability P. Recall that $(X_n)_{n\ge0}$ is said to be w-geometrically ergodic if there exist an invariant distribution ν on E such that $\nu(w) < +\infty$, and some constants $r < 1$ and $D \in \mathbb{R}_+$ such that for every $f \in \mathcal{B}_w$ we have

$$\left\| P^n f - \nu(f) 1_E \right\|_w \le D r^n \|f\|_w.$$

Corollary 1. *Assume that* $(X_n)_{n\ge0}$ *is an aperiodic positive Harris Markov chain with stationary distribution* ν. *Then* $(X_n)_{n\ge0}$ *is* w-*geometrically ergodic if and only if one of the two next conditions holds*:

(a) $\forall f \in \mathcal{B}_w$, $P^n f \to \nu(f) 1_E$ *in* $\mathcal{B}_w$ *when* $n \to +\infty$.
(b) *For all* $f \in \mathcal{B}_w$, $(\frac{1}{n}\sum_{k=1}^n P^k f)_n$ *contains a subsequence converging in* $\mathcal{B}_w$ *to* $\nu(f) 1_E$.

Corollary 1 is an easy consequence of Theorem 1. (When (b) is assumed, the aperiodicity condition ensures that $\lambda = 1$ is the unique peripheral eigenvalue of P.)

The reader will find in [10] many examples of geometrically ergodic Markov chains. Geometric ergodicity with a bounded function w corresponds to an aperiodic Markov chain satisfying Doeblin's condition.

When w is unbounded and $(X_n)_{n\ge 0}$ is aperiodic and ψ-irreducible w.r.t. to some σ-finite positive measure ψ on E, w-geometric ergodicity is equivalent to the following drift condition [10] (Chapter 16): there exist $\rho < 1$, $L > 0$, and a petite set A in E such that $Pw_0 \le \rho w_0 + L1_A$, where w_0 is a function on E such that $d^{-1}w \le w_0 \le dw$ for some constant $d > 0$. Corollary 1 sheds new light on this fact, at least for countable Markov chains, and as an illustration, let us present a simple proof of the well-known next statement proved in [5].

Corollary 2. *Let $(X_n)_{n\ge 0}$ be an aperiodic and irreducible Markov chain with state space $E = \mathbb{N}$, and suppose $\lim_k w(k) = +\infty$. Then $(X_n)_{n\ge 0}$ is w-geometrically ergodic if and only if there exist $\rho < 1$ and $C > 0$ such that $P^n w \le C\rho^n w + C$ for all $n \ge 1$.*

By using the basic arguments of [10] (Section 16.1.1), one can easily see that the condition in Corollary 2 is equivalent to: $\exists \rho < 1, \exists L > 0$, $Pw_0 \le \rho w_0 + L$, with w_0 equivalent to w.

Proof of Corollary 2. If $(X_n)_{n\ge 0}$ is w-geometrically ergodic, then $P^n w \le Dr^n w + \nu(w)$. Conversely, suppose $P^n w \le C\rho^n w + C$ with $\rho < 1$, $C > 0$, independent of n. Then we have $\sup_{n\ge 1} \|P^n\|_w \le 2C$, and there exists an invariant distribution ν such that $\nu(w) < +\infty$.[3] Set $\Pi_n = \frac{1}{n}\sum_{k=1}^n P^k$, and let $\ell^1(\nu)$ be the space of $\mathbb{C}$-valued sequences $(x(n))_{n\in\mathbb{N}}$ such that $\sum_n \nu(n)|x(n)| < +\infty$. P is a contraction of $\ell^1(\nu)$, so for any $f \in \ell^1(\nu)$, $(\Pi_n f)_n$ converges in $\ell^1(\nu)$, use e.g. [2] (Section VIII.5). The limit $\alpha = \lim_n \Pi_n f$ is P-invariant, and by irreducibility, it is constant: $\forall i \in \mathbb{N},\ \alpha(i) = \nu(f)$. Thus $\lim_n \Pi_n f(i) = \nu(f)$ for all $i \in \mathbb{N}$.

Now let $f \in \mathcal{B}_w$, and for convenience assume $\|f\|_w = 1$ (i.e. $|f| \le w$). We have

$$\forall i \in \mathbb{N}, \quad \left|P^k f(i) - \nu(f)\right| \le P^k w(i) + \nu\left(|f|\right) \le C\rho^k w(i) + C + \nu(w).$$

Let $\varepsilon > 0$. Then there exist $i_0 \ge 1$, $N_0 \ge 1$ such that $w(i)^{-1}|P^k f(i) - \nu(f)| \le \varepsilon$ for all $i > i_0$ and $k > N_0$. By using the fact that $\sup_{k\ge 1} \|P^k w\|_w < +\infty$ and

$$\Pi_n f(i) - \nu(f) = \frac{1}{n}\sum_{k=0}^{N_0}\left(P^k f(i) - \nu(f)\right) + \frac{1}{n}\sum_{k=N_0+1}^{n}\left(P^k f(i) - \nu(f)\right),$$

we easily deduce that there exists $N_1 \ge N_0$ such that $w(i)^{-1}|\Pi_n f(i) - \nu(f)| \le 2\varepsilon$ for all $i > i_0$ and $n > N_1$. Finally let $N_2 \ge N_1$ be such that $w(i)^{-1}|\Pi_n f(i) - \nu(f)| \le 2\varepsilon$ for all $i = 0, \ldots, i_0$ and $n > N_2$. Then $\|\Pi_n f - \nu(f)\|_w \le 2\varepsilon$ for all $n > N_2$, and Corollary 1 then applies. □

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[3] This is a classical fact: consider the distributions $\mu_n(A) = \frac{1}{n}\sum_{k=1}^n (P^k 1_A)(x_0)$ ($x_0 \in E$ is fixed). From $P^n w \le C\rho^n w + C$, we easily obtain $\sup_{n\ge 1} \mu_n(w) \le 2Cw(x_0) < +\infty$, so $(\mu_n)_n$ is tight (use $\lim_k w(k) = +\infty$), and one can select a subsequence converging to an invariant distribution ν such that $\nu(w) < +\infty$.

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