WEAK LAW OF LARGE NUMBERS FOR ADAPTED DOUBLE ARRAYS OF RANDOM VARIABLES

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Abstract. The aim of this paper is to extend the “classical degenerate convergence criterion” and the Feller weak law of large numbers to double adapted arrays of random variables.

1. Introduction

The celebrated Feller weak law of large numbers (WLLN) say that if $X_1, X_2, \ldots$ is a sequence of independent and identically distributed (i.i.d.) random variables satisfying $nP(|X_1| > n) = o(1)$, then $\sum_{i=1}^{n} \left(X_i - \mathbb{E}X_1I(|X_1| \leq n)\right)/n \rightarrow 0$ in probability as $n \rightarrow \infty$.

The basis for proving weak laws is the "classical degenerate convergence criterion":

Theorem 1.1 ([10], p. 290). Let $X_1, X_2, \ldots$ be independent random variables with partial sums $\{S_n, n \geq 1\}$, and let $\{b_n, n \geq 1\}$ a sequence of reals, $b_n \uparrow \infty$ as $n \rightarrow \infty$. Then, writing $X_{ni} = X_iI(|X_i| \leq b_n), 1 \leq i \leq n$, we have that

\begin{equation}
\frac{1}{b_n}S_n \overset{P}{\rightarrow} 0 \text{ as } n \rightarrow \infty
\end{equation}

if and only if

\begin{align}
\sum_{i=1}^{n} P(|X_i| > b_n) &\rightarrow 0 \quad \text{(1.2)} \\
\frac{1}{b_n} \sum_{i=1}^{n} \mathbb{E}X_{ni} &\overset{P}{\rightarrow} 0 \quad \text{(1.3)} \\
\frac{1}{b_n^2} \sum_{i=1}^{n} \mathbb{V}arX_{ni} &\rightarrow 0 \quad \text{(1.4)}
\end{align}

This theorem was extended in [9].

Received October 13, 2006; Revised April 23, 2007.

2000 Mathematics Subject Classification. 60F05, 60G50, 60G42.

Key words and phrases. double adapted array of random variables, weak law of large numbers, convergence in probability, martingale difference, sum of i.i.d. random variables.

This work was supported in part by the National Science Council of Vietnam No 100706.

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Theorem 1.2 ([9], pp. 29–30). Let \( S_n = \sum_{i=1}^{n} X_i, F_n, n \geq 1 \) be a martingale and let \( \{b_n, n \geq 1\} \) be a sequence of positive constants with \( b_n \uparrow \infty \) as \( n \to \infty \). Then, writing \( X_{ni} = X_i I\{|X_i| \leq b_n\}, 1 \leq i \leq n \), we have that

(1.5) \[ b_n^{-1} S_n \overset{P}{\to} 0 \text{ as } n \to \infty \]

if

(1.6) \[ \sum_{i=1}^{n} P(|X_i| > b_n) \to 0 \]

(1.7) \[ b_n^{-1} \sum_{i=1}^{n} E(X_{ni}|F_{i-1}) \overset{P}{\to} 0 \]

(1.8) \[ b_n^{-2} \sum_{i=1}^{n} \{E X_{ni}^2 - E[E(X_{ni}|F_{i-1})]^2\} \to 0. \]

Note here that in the general case, when \( X_i \) are not independent, then the reverse is not true. (see [9] pp. 29–30).

The WLLN has been extended to the arrays of random variables or random elements (for random variables, see Hong and Lee [5], Hong and Oh [6], Sung [11] and Sung et al. [12], and for random elements, see Adler et al. [1], Ahmed et al. [2], Hong et al. [7] and Sung et al. [13]).

The aim of this paper is to extend the “classical degenerate convergence criterion” and the Feller weak law of large numbers to double adapted arrays of random variables.

2. Preliminaries

In this section, notation, technical definitions and lemmas needed in connection with the main results will be presented. Some of the lemmas may be of independent interest.

For \( a, b \in \mathbb{R} \), \( \max\{a, b\} \) will be denoted by \( a \vee b \). Throughout this paper, the symbol \( C \) will denote a generic constant \( (0 < C < \infty) \) which is not necessarily the same one in each appearance.

Let \( \mathbb{N} \) denote the set of all positive integers. As in [8], we note \( \prec \) the lexicographic order on \( \mathbb{N} \times \mathbb{N} \), i.e., \((i, j) \prec (k, l)\) if and only if either \( i < k \) or \( i = k \) and \( j < l \).

Let \((\Omega, \mathcal{F}, P)\) be a probability space. Then, a double array \( \{F_{mn}, m \geq 1, n \geq 1\} \) of sub-\(\sigma\)-algebras of \( \mathcal{F} \) with indices in \( \mathbb{N} \times \mathbb{N} \) will be called a stochastic basis if it is increasing, i.e., \( F_{ij} \subset F_{kl} \) for \((i,j) \prec (k,l)\). If \( \{F_{mn}, m \geq 1, n \geq 1\} \) is a stochastic basis and \( X_{mn} \) is an \( F_{mn} \)-measurable random variable for each \((m,n) \in \mathbb{N} \times \mathbb{N} \), then \( \{X_{mn}, F_{mn}, m \geq 1, n \geq 1\} \) is called an adapted double array.
An adapted double array \( \{ X_{mn}, F_{mn}, m \geq 1, n \geq 1 \} \) is called rowwise martingale difference if it is martingale difference in each row, i.e., for each \( m \in \mathbb{N} \)

\[
E(X_{m,n+1}|F_{mn}) = 0 \quad \text{almost surely (a.s.), } \forall n \in \mathbb{N}.
\]

**Remark 1.** It is easy to show that if \( \{ X_{mn}, F_{mn} \} \) is a rowwise martingale difference, then for all \((i, j) \prec (r, s)\), we have \( E(X_{rs}|F_{ij}) = 0 \) a.s.

Random variables \( \{ X_{mn}, m \geq 1, n \geq 1 \} \) are said to be stochastically dominated by a random variable \( X \) if for some constant \( C < \infty \)

\[
P\{|X_{mn}| > t\} \leq C P\{|X| > t\}, \quad t \geq 0, m \geq 1, n \geq 1.
\]

An array of positive numbers \( (b_{mn}) \) will be called increasing to \( +\infty \) if

\[
b_{ij} < b_{rs} \text{ if and only if } (i, j) \prec (r, s) \text{ and } b_{mn} \uparrow \infty \text{ as } m \lor n \to \infty.
\]

**Lemma 2.1.** Let \( \{ X_{mn}, F_{mn}, m \geq 1, n \geq 1 \} \) be an adapted double array. Then \( \{ Y_{mn} = X_{mn} - E(X_{mn}|F_{m,n-1}), F_{mn} \} \) is a rowwise martingale difference.

**Proof.** Indeed, since \( E(X_{m,n+1}|F_{mn}) \) is an \( F_{mn} \)-measurable, we have

\[
E(Y_{m,n+1}|F_{mn}) = E(X_{m,n+1} - E(X_{m,n+1}|F_{mn})|F_{mn})
= E(X_{m,n+1}|F_{mn}) - E(X_{m,n+1}|F_{mn}) = 0.
\]

\( \square \)

**Lemma 2.2.** Let \( \{ X_{mn}, F_{mn} \} \) be a rowwise martingale difference and \( E X_{mn}^2 < \infty \) for all \( m, n \in \mathbb{N} \times \mathbb{N} \). Then

\[
E\left(\sum_{i=1}^{m} \sum_{j=1}^{n} X_{ij}\right)^2 = \sum_{i=1}^{m} \sum_{j=1}^{n} E X_{ij}^2.
\]

**Proof.** For all \((i, j), (k, l) \in \mathbb{N} \times \mathbb{N}, (i, j) \neq (k, l)\), we can assume that \((i, j) \prec (k, l)\). Then

\( F_{ij} \subset F_{kl} \)

and

\[
E(X_{ij}X_{kl}) = E\{E(X_{ij}X_{kl}|F_{ij})\}
= E\{X_{ij}E(X_{kl}|F_{ij})\}
= E(X_{ij} \cdot 0) = 0.
\]

From that point, we yield the conclusion. \( \square \)

**Lemma 2.3.** For all \( k \in \mathbb{N}, k \geq 1 \), the following inequalities hold.

1. \( k^{2/p} \leq \frac{2}{\rho} \sum_{r=1}^{k} r^{2-1} \) for \( \rho \in (0, 2) \).
2. \( \sum_{r=r_0}^{k} r^{\frac{2}{\rho} - 2} \leq \frac{1}{2p} (k^{\frac{2}{\rho} - 1} - (r_0 - 1)^{\frac{2}{\rho} - 1}) \) for all \( r_0 \in \mathbb{N}, \rho \in (1, 2) \).
Proof. 1) For \( \rho \in (0, 2) \) then \( \frac{2}{\rho} - 1 > 0 \) and function \( y = x^{2-1} \) is increasing on \( (0, \infty) \). Hence
\[
r^{2-1} \geq \int_{r-1}^{r} x^{2-1} \, dx \quad \text{for all } r = 1, 2, \ldots, k.
\]
So
\[
\frac{2}{\rho} \sum_{r=1}^{k} r^{2-1} \geq \frac{2}{\rho} \int_{0}^{k} x^{2-1} \, dx = k^{2}.
\]
2) For \( \rho \in (1, 2) \) then \( \frac{2}{\rho} - 2 < 0 \). Hence, function \( y = x^{\frac{2}{\rho}-2} \) is decreasing on \( (0, \infty) \) and
\[
r^{\frac{2}{\rho}-2} \leq \int_{r-1}^{r} x^{\frac{2}{\rho}-2} \, dx \quad \text{for all } r = r_0, r_0 + 1, \ldots, k; r_0 \in \mathbb{N}.
\]
Eventually,
\[
\sum_{r=r_0}^{k} r^{\frac{2}{\rho}-2} \leq \sum_{r=r_0}^{k} \int_{r-1}^{r} x^{\frac{2}{\rho}-2} \, dx = \frac{\rho}{2 - \rho} \{ k^{\frac{2}{\rho}-1} - (r_0 - 1)^{\frac{2}{\rho}-1} \}
\]
for all \( r_0 \in \mathbb{N}, \rho \in (1, 2) \).

The proof is complete. \( \square \)

3. Main results

With the notations and lemmas as above, the main results can now be established.

**Theorem 3.1.** Let \( \{X_{mn}, \mathcal{F}_{mn}, m \geq 1, n \geq 1\} \) be an adapted double array, \( (b_{mn}) \) be an array of positive numbers increasing to \( +\infty \). Put \( Y_{ij} = X_{ij} I \{|X_{ij}| \leq b_{mn}\} \). Then we have

\[
(3.1) \quad \frac{1}{b_{mn}} \sum_{i=1}^{m} \sum_{j=1}^{n} X_{ij} \xrightarrow{P} 0 \quad \text{as } m \lor n \to \infty,
\]

if

\[
(3.2) \quad \text{i) } \sum_{i=1}^{m} \sum_{j=1}^{n} \mathbb{P}\{|X_{ij}| > b_{mn}\} \to 0 \quad \text{as } m \lor n \to \infty,
\]

\[
(3.3) \quad \text{ii) } \frac{1}{b_{mn}} \sum_{i=1}^{m} \sum_{j=1}^{n} \mathbb{E}\{Y_{ij}|\mathcal{F}_{i,j-1}\} \xrightarrow{P} 0 \quad \text{as } m \lor n \to \infty,
\]
iii) \( \frac{1}{b_{mn}^2} \sum_{i=1}^{m} \sum_{j=1}^{n} \{ EY_{ij}^2 - E(E(Y_{ij}|\mathcal{F}_{i,j-1}))^2 \} \to 0 \) as \( m \vee n \to \infty \).

Proof. For \( m \geq 1, n \geq 1 \), we put
\[
S_{mn} = \sum_{i=1}^{m} \sum_{j=1}^{n} X_{ij},
\]
\[
\tilde{S}_{mn} = \sum_{i=1}^{m} \sum_{j=1}^{n} Y_{ij},
\]
\[
\mu_{mn} = \sum_{i=1}^{m} \sum_{j=1}^{n} E(Y_{ij}|\mathcal{F}_{i,j-1}).
\]

On account of (i),
\[
P(S_{mn}/b_{mn} \neq \tilde{S}_{mn}/b_{mn}) = P(S_{mn} \neq \tilde{S}_{mn}) \leq \sum_{1 \leq i \leq m, 1 \leq j \leq n} P(Y_{ij} \neq X_{ij}) \leq \sum_{i=1}^{m} \sum_{j=1}^{n} P(|X_{ij}| > b_{mn}) \to 0 \text{ as } m \vee n \to \infty.
\]

And so it suffices to prove that \( \frac{1}{b_{mn}} \tilde{S}_{mn} \to 0 \). But on account of (ii),
\[
\frac{1}{b_{mn}} \mu_{mn} \to 0 \text{ as } m \vee n \to \infty,
\]
so that it suffices to prove that
\[
\frac{1}{b_{mn}}(\tilde{S}_{mn} - \mu_{mn}) \to 0 \text{ as } m \vee n \to \infty.
\]

For \( \epsilon > 0 \), from Chebyshev’s inequality together with Lemmas 2.1, 2.2, and (iii), we have
\[
P\{|\frac{1}{b_{mn}}(\tilde{S}_{mn} - \mu_{mn})| > \epsilon\} = P\{|\frac{1}{b_{mn}} \sum_{i=1}^{m} \sum_{j=1}^{n} (Y_{ij} - E(Y_{ij}|\mathcal{F}_{i,j-1}))| > \epsilon\} \leq \frac{1}{\epsilon^2} E\{\frac{1}{b_{mn}} \sum_{i=1}^{m} \sum_{j=1}^{n} (Y_{ij} - E(Y_{ij}|\mathcal{F}_{i,j-1}))^2\}^2
\]
\[
= \frac{1}{b_{mn}^2} \sum_{i=1}^{m} \sum_{j=1}^{n} E(Y_{ij} - E(Y_{ij}|\mathcal{F}_{i,j-1}))^2
\]

\[
\begin{align*}
&= \frac{1}{b_{mn}^2} \sum_{i=1}^{m} \sum_{j=1}^{n} \left\{ E(Y_{ij}^2) - E(E(Y_{ij}|\mathcal{F}_{i,j-1}))^2 \right\} \\
&\to 0 \text{ as } m \vee n \to \infty.
\end{align*}
\]

The proof is completed. \(\square\)

It is easy to show that if \(X_{mn} \overset{P}{\to} X\) as \(m \vee n \to \infty\), then \(X_{1n} \overset{P}{\to} X\) as \(n \to \infty\) and we get

**Corollary 3.2.** Let \(\{S_n = \sum_{i=1}^{n} X_i, \mathcal{F}_n, n \geq 1\}\) be an adapted sequence and let \(\{b_n, n \geq 1\}\) be a sequence of positive constants with \(b_n \uparrow \infty\) as \(n \to \infty\). Then, writing \(X_{ni} = X_i I(|X_i| \leq b_n), 1 \leq i \leq n\), we have that

\[
(3.5) \quad b_{n}^{-1} S_n \overset{P}{\to} 0 \text{ as } n \to \infty
\]

if

\[
(3.6) \quad \begin{align*}
&\text{i) } \sum_{i=1}^{n} P(|X_i| > b_n) \to 0 \\
&\text{ii) } b_{n}^{-1} \sum_{i=1}^{n} E(X_{ni}|\mathcal{F}_{i-1}) \overset{P}{\to} 0 \\
&\text{iii) } b_{n}^{-2} \sum_{i=1}^{n} [E X_{ni}^2 - E(E(X_{ni}|\mathcal{F}_{i-1}))^2] \to 0.
\end{align*}
\]

Thus, Theorem 1.2 is also true if the martingale condition of \((S_n = \sum_{i=1}^{n} X_i, \mathcal{F}_n)\) is replaced by the weaker condition: \((S_n = \sum_{i=1}^{n} X_i, \mathcal{F}_n)\) is an adapted sequence. The below example shows that the above corollary is really stronger than the theorem 1.2.

Let \((Y_i)\) be a sequence of independent and identically distributed random variables such that

\[
P(Y_i = -1) = P(Y_i = 1) = \frac{1}{2}.
\]

Then \(EY_i = 0 \quad (\forall i = 1, 2, \ldots)\). Applying the Feller weak law of large numbers to \((Y_i)\), we have

\[
\frac{1}{n} \sum_{i=1}^{n} Y_i \overset{a.s.}{\to} 0 \text{ as } n \to \infty.
\]

(In fact \(\frac{1}{n} \sum_{i=1}^{n} Y_i \overset{P}{\to} 0 \text{ as } n \to \infty\).)

Put

\[
X_i = Y_i + \frac{1}{i}.
\]

Then \(EX_i = \frac{1}{i} \quad (\forall i = 1, 2, \ldots)\) and

\[
\frac{1}{n} \sum_{i=1}^{n} X_i = \frac{1}{n} \sum_{i=1}^{n} Y_i + \frac{1}{n} \sum_{i=1}^{n} \frac{1}{i} \overset{P}{\to} 0 + 0 = 0 \text{ as } n \to \infty.
\]
Thus, \((S_n = \sum_{i=1}^{n} X_i)\) satisfies the condition (1.1) and by Theorem 1.1, it also satisfies the conditions (1.2), (1.3), (1.4) (with \(b_n = n\)).

Now, let \(\mathcal{F}_n\) be the \(\sigma\)-field generated by \((X_i; 1 \leq i \leq n)\). By the independence of \((X_i)\) the conditions (1.2), (1.3), (1.4) can be replaced by the conditions (3.6), (3.7), (3.8), respectively. Then \((S_n = \sum_{i=1}^{n} X_i; : \mathcal{F}_n)\) satisfies all assumptions of Corollary 3.2. On the other hand, \((S_n = \sum_{i=1}^{n} X_i; : \mathcal{F}_n)\) is not a martingale. This shows that the martingale condition of \((S_n = \sum_{i=1}^{n} X_i; : \mathcal{F}_n)\) in Theorem 1.2 is too strong.

**Corollary 3.3.** Let array of random variables \(\{X_{mn}, m \geq 1, n \geq 1\}\) be independent, and let \(\{b_{mn}, m \geq 1, n \geq 1\}\) be an array of positive numbers increasing to \(+\infty\). Put \(Y_{ij} = X_{ij} I\{|X_{ij}| \leq b_{mn}\}\). Then we have

\[
\text{(3.9)} \quad \frac{1}{b_{mn}} \sum_{i=1}^{m} \sum_{j=1}^{n} X_{ij} \xrightarrow{p} 0 \quad \text{as} \quad m \vee n \to \infty
\]

if

\[
\text{(3.10)} \quad \text{i) } \sum_{i=1}^{m} \sum_{j=1}^{n} P\{|X_{ij}| > b_{mn}\} \to 0 \quad \text{as} \quad m \vee n \to \infty,
\]

\[
\text{(3.11)} \quad \text{ii) } \frac{1}{b_{mn}} \sum_{i=1}^{m} \sum_{j=1}^{n} EY_{ij} \to 0 \quad \text{as} \quad m \vee n \to \infty,
\]

\[
\text{(3.12)} \quad \text{iii) } \frac{1}{b_{mn}^{2}} \sum_{i=1}^{m} \sum_{j=1}^{n} \text{Var}Y_{ij} \to 0 \quad \text{as} \quad m \vee n \to \infty.
\]

**Proof.** For each \((m, n) \in \mathbb{N} \times \mathbb{N}\), let \(\mathcal{F}_{mn}\) be the \(\sigma\)-algebra generated by all the elements \(X_{ij}\), where \((i, j) \prec (m, n)\) or \((i, j) = (m, n)\). Then, array \(\{\mathcal{F}_{mn}, m \geq 1, n \geq 1\}\) is a stochastic basis and \(X_{mn}\) is an \(\mathcal{F}_{mn}\)-measurable random variable for each \((m, n) \in \mathbb{N} \times \mathbb{N}\).

From the hypothesis, we have that array \(\{X_{mn}, m \geq 1, n \geq 1\}\) is independent. For this reason, these conditions (3.2), (3.3), and (3.4) in Theorem 3.1, correspondingly, change to (3.10), (3.11) and (3.12) in Corollary 3.3. Hence, the proof is clear. \(\square\)

We shall now prove the following extension of the well-known Feller theorem for adapted double arrays. This theorem also is extended by Gut in the case of sequences (see [4]).

**Theorem 3.4.** Let \(\{X_{mn}; \mathcal{F}_{mn}, m \geq 1, n \geq 1\}\) be an adapted double array. Suppose that \(\{X_{mn}; m \geq 1, n \geq 1\}\) is stochastically dominated by a random variable \(X\). Let real number \(\rho \in (0, 2)\). Put \(Y_{ij} = X_{ij} I\{|X_{ij}| \leq m^{\frac{1}{\rho}} n^{\frac{1}{\rho}}\}\).

If

\[
\lim_{r \to \infty} r P\{|X| > r^{\frac{1}{\rho}}\} = 0,
\]

then \(\ldots\)
then the WLLN

$$\frac{\sum_{i=1}^{m} \sum_{j=1}^{n} (X_{ij} - \mathbb{E}(Y_{ij}|F_{i,j-1}))}{m^{\frac{1}{\rho}} n^{\frac{1}{\rho}}} \to 0 \quad \text{as} \quad m \vee n \to \infty$$

obtains.

Proof. We verify the conditions (3.2) and (3.4) in turn, where \( b_{mn} = m^{\frac{1}{\rho}} n^{\frac{1}{\rho}} \).

We first verify the condition (3.2). By the assumption \( \{X_{mn}, m \geq 1, n \geq 1\} \) is stochastically dominated by a random variable \( X \), we have

$$\sum_{i=1}^{m} \sum_{j=1}^{n} P(|X_{ij}| > m^{\frac{1}{\rho}} n^{\frac{1}{\rho}}) \leq C \sum_{i=1}^{m} \sum_{j=1}^{n} P(|X| > m^{\frac{1}{\rho}} n^{\frac{1}{\rho}})$$

$$= CmnP(|X| > m^{\frac{1}{\rho}} n^{\frac{1}{\rho}}) \to 0 \quad \text{as} \quad m \vee n \to \infty.$$  \hfill (3.13)

Next, we verify the condition (3.4). We have

$$0 \leq m^{\frac{2}{\rho}} n^{\frac{2}{\rho}} \sum_{i=1}^{m} \sum_{j=1}^{n} \{ \mathbb{E}Y_{ij}^2 - \mathbb{E} (\mathbb{E}(Y_{ij}|F_{i,j-1}))^2 \}$$

$$\leq m^{\frac{2}{\rho}} n^{\frac{2}{\rho}} \sum_{i=1}^{m} \sum_{j=1}^{n} \mathbb{E}Y_{ij}^2$$

$$= m^{\frac{2}{\rho}} n^{\frac{2}{\rho}} \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=1}^{\infty} \mathbb{E} \left\{ X_{ij}^2 I\{k^{-1/\rho} < |X_{ij}| \leq k^{1/\rho}\} \right\}$$

$$\leq m^{\frac{2}{\rho}} n^{\frac{2}{\rho}} \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=1}^{\infty} k^{2/\rho} \mathbb{P}\{(k-1)^{1/\rho} < |X_{ij}| \leq k^{1/\rho}\}.$$

$$\leq Cm^{\frac{2}{\rho}} n^{\frac{2}{\rho}} \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=1}^{\infty} \sum_{r=1}^{k} \mathbb{P}\{(k-1)^{1/\rho} < |X_{ij}| \leq k^{1/\rho}\}$$

$$= Cm^{\frac{2}{\rho}} n^{\frac{2}{\rho}} \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{r=1}^{m} \mathbb{P}\{(k-1)^{1/\rho} < |X_{ij}| \leq k^{1/\rho}\} \sum_{k=r}^{mn}$$

$$= Cm^{\frac{2}{\rho}} n^{\frac{2}{\rho}} \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{r=1}^{m} \mathbb{P}\{(r-1)^{1/\rho} < |X_{ij}| \leq (mn)^{1/\rho}\}$$

$$\leq Cm^{\frac{2}{\rho}} n^{\frac{2}{\rho}} \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{r=1}^{m} \mathbb{P}\{|X_{ij}| > (r-1)^{1/\rho}\}.$$
\[ \leq Cm^{-2}n^{-2} \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{r=1}^{mn} r^{\frac{2}{\rho}} - 1 P\{|X| > (r - 1)^{1/\rho}\} \]

\[ = Cm^{-2}n^{-2} mn \sum_{r=1}^{mn} r^{\frac{2}{\rho}} - 2 r P\{|X| > (r - 1)^{1/\rho}\} \]

\[ = C(mn)^{\frac{2}{\rho} + 1} \sum_{r=1}^{mn} r^{\frac{2}{\rho} - 2} \left\{ r P\{|X| > (r - 1)^{1/\rho}\} \right\}. \]

It remains to prove the last term

\[ (mn)^{\frac{2}{\rho} + 1} \sum_{r=1}^{mn} r^{\frac{2}{\rho} - 2} \left\{ r P\{|X| > (r - 1)^{1/\rho}\} \right\} \]

converges to 0 as \( m \vee n \to \infty \).

In the case of \( 0 < \rho \leq 1 \), we have \( r^{\frac{2}{\rho} - 2} \leq (mn)^{\frac{2}{\rho} - 2} \) for all \( r = 1, 2, \ldots, mn \).
So, by the fact \( \lim_{r \to \infty} r P\{|X| > (r - 1)^{1/\rho}\} = 0 \) and Stolz's theorem, we have

\[ (mn)^{\frac{2}{\rho} + 1} \sum_{r=1}^{mn} r^{\frac{2}{\rho} - 2} \left\{ r P\{|X| > (r - 1)^{1/\rho}\} \right\} \]

\[ \leq \frac{\sum_{r=1}^{mn} r P\{|X| > (r - 1)^{1/\rho}\}}{mn} \to 0 \text{ as } m \vee n \to \infty. \]

Consider now the case \( 1 < \rho < 2 \).
By the fact \( \lim_{r \to \infty} r P\{|X| > (r - 1)^{1/\rho}\} = 0 \) again, for any \( \epsilon > 0 \), there exists \( r_0 \in \mathbb{N} \) such that

\[ r P\{|X| > (r - 1)^{1/\rho}\} < \epsilon \text{ for all } r \geq r_0. \]

Then, we have

\[ (mn)^{\frac{2}{\rho} + 1} \sum_{r=1}^{mn} r^{\frac{2}{\rho} - 2} \left\{ r P\{|X| > (r - 1)^{1/\rho}\} \right\} \]

\[ = (mn)^{\frac{2}{\rho} + 1} \left\{ \sum_{r=1}^{r_0 - 1} r^{\frac{2}{\rho} - 2} \left\{ r P\{|X| > (r - 1)^{1/\rho}\} \right\} \right\} \]

\[ + \sum_{r=r_0}^{mn} r^{\frac{2}{\rho} - 2} \left\{ r P\{|X| > (r - 1)^{1/\rho}\} \right\} \]

\[ \leq C \frac{1}{(mn)^{\frac{2}{\rho}}} + (mn)^{\frac{2}{\rho} + 1} \sum_{r=r_0}^{mn} r^{\frac{2}{\rho} - 2} \epsilon \]

\[ = C \frac{1}{(mn)^{\frac{2}{\rho}}} + \epsilon (mn)^{\frac{2}{\rho} + 1} \sum_{r=r_0}^{mn} r^{\frac{2}{\rho} - 2}. \]
Note that
\[
\lim_{m \vee n \to \infty} \frac{1}{(mn)^{2-\rho}} = 0
\]
and by Lemma 2.3
\[
\epsilon(mn)^{2-\rho} \sum_{r=1}^{mn} r^{2} - 2 \rho < \epsilon(mn)^{2-\rho} = \epsilon' \quad \text{for all } mn > r_0.
\]
Thus
\[
(mn)^{2-\rho} \sum_{r=1}^{mn} r^{2} - 2 \rho < \epsilon' \quad \text{as } m \vee n \to \infty.
\]
Combining (3.13) and (3.14) we complete the proof. \(\square\)

**Corollary 3.5.** Let \(\{X_n, F_n, n \geq 1\}\) be an adapted sequence. Suppose that \(\{X_n, n \geq 1\}\) is stochastically dominated by a random variable \(X\). Let real number \(\rho \in (0, 2)\). Put \(Y_i = X_i I\{|X_i| \leq n^{\frac{1}{\rho}}\}\).

If
\[
\lim_{r \to \infty} r P\{|X| > r^{\frac{1}{\rho}}\} = 0,
\]
then the WLLN
\[
\sum_{i=1}^{n} \left( X_i - E\{Y_i| F_{i-1}\} \right) \frac{1}{n^{\frac{1}{\rho}}} \to 0 \quad \text{as } n \to \infty
\]
obtains.

**Corollary 3.6.** Suppose that \(X, X_1, X_2, \ldots\) are identically distributed, independent random variables, the real number \(\rho \in (0, 2)\).

If
\[
\lim_{r \to \infty} r P\{|X| > r^{\frac{1}{\rho}}\} = 0,
\]
then the WLLN
\[
\sum_{i=1}^{n} \left( X_i - E\{X I(|X| \leq n^{\frac{1}{\rho}})\} \right) \frac{1}{n^{\frac{1}{\rho}}} \to 0 \quad \text{as } n \to \infty
\]
obtains.

In the special case, when \(\rho = 1\) we get the Feller’s weak law of large numbers.

**References**


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