

Strong Limit Theorems for Dependent Random Variables

Libin Wu, Bainian Li,

Abstract—In This Article We establish moment inequality of dependent random variables, furthermore some theorems of strong law of large numbers and complete convergence for sequences of dependent random variables. In particular, independent and identically distributed Marcinkiewicz Law of large numbers are generalized to the case of m_0 -dependent sequences.

Keywords—Lacunary System, Generalized Gaussian, NA sequences, strong law of large numbers.

I. INTRODUCTION

LET X_1, X_2, \dots denote a sequence of random variables defined on a fixed probability space (Ω, F, P) . The partial sums of the random variables are $S_n = \sum_{i=1}^n X_i$, for $n \geq 1$ and $S_0 = 0$,

$$S_{b,n} = \sum_{i=b+1}^{b+n} X_i, S(i, j) = \sum_{k=i}^j X_k, 1 \leq i \leq j.$$

Definition 1.1 (Fazekas and Klesov, 2000, p. 447) [1] A sequence of random variables $\{X_n, n \geq 1\}$ is said to have the r th ($r > 0$) moment function of superadditive structure if there exists a non-negative function $g(i, j)$ of two arguments such that for all $b \geq 0$ and $1 \leq k \leq k+l$,

$$g(b, k) + g(b+k, l) \leq g(b, k+l) \quad (1)$$

$$E|S_{b,n}|^r \leq g^\alpha(b, n), n \geq 1, \text{ for some } \alpha > 1 \quad (2)$$

Definition 1.2 Let X be a real-valued random variable, we call a Locally Generalized Gaussian, If there exists $\alpha > 0$, such that

$$E(\exp(uX)|F) \leq \exp(u^2\alpha^2/2) \quad a.s. \quad (3)$$

for any $u \in R$.

Definition 1.3 Given $p > 0$, a sequence of real-valued random variables $\{X_n, n \geq 1\}$ is called a Lacunary System or an S_p system, if there exists a positive constant K_p such that

$$E|\sum_{i=m}^n C_i X_i|^p \leq K_p (\sum_{i=m}^n C_i^2)^{p/2}$$

for any sequence of real constant $\{C_i\}$ and all $n \geq m$.

Definition 1.4 The random variables X_1, X_2, \dots, X_n are said to be negatively associated if for every n and every pair of disjoint subsets A_1, A_2 of $\{1, 2, \dots, n\}$

$$\text{Cov}(f_1(X_i : i \in A_1), f_2(X_j : j \in A_2)) \leq 0,$$

Libin Wu, School of Stat & Applied mathematics Anhui University of Finance and Economics, Bengbu 233030, PR China (e-mail: wlb1158@163.com).

Bainian Li, School of Stat & Applied mathematics Anhui University of Finance and Economics, Bengbu 233030, PR China (e-mail: libainian49@163.com)

Manuscript received March 19, 2011.

whenever f_1 and f_2 are coordinatewise increasing and this covariance exists.

Definition 1.5 A stationary sequence $\{X_n\}$ is called m_0 -dependent for a given fixed m_0 if (X_1, \dots, X_i) and (X_j, X_{j+1}, \dots) are independent whenever $j-i > m_0$.

Lemma 1.1 (Dini Theorem, Fikhtengolts, 1954, p. 286) [2] Let c_1, c_2, \dots be non-negative numbers, $v_n = \sum_{k=n}^{\infty} c_k$, if $0 < v_n < \infty$ for $n \geq 1$, then

$$\sum_{n=1}^{\infty} \frac{c_n}{v_n^\delta} < \infty, (0 < \delta < 1). \quad (4)$$

Lemma 1.2 (Hu, 2005, Theorem 2.1) [3] We assume that $(X_n, n \geq 1)$ has the r th moment function of superadditive structure, $g(0, n) = g_n$ and g_n non-decreases, $\{b_n\}$ is a non-decreasing unbounded sequence of positive numbers and

$$\sum_{n=1}^{\infty} \frac{g_n^\alpha - g_{n-1}^\alpha}{b_n^r} < \infty,$$

then

$$\lim_{n \rightarrow \infty} \frac{S_n}{b_n} = 0 a.s. \quad (5)$$

and with the growth rate

$$\frac{S_n}{b_n} = O\left(\frac{\beta_n}{b_n}\right) a.s., \quad (6)$$

where

$$\beta_n = \max_{1 \leq k \leq n} b_k v_k^{\frac{\delta}{r}}, 0 < \delta < 1,$$

$$v_n = \sum_{k=n}^{\infty} \frac{\alpha_k}{b_k^r}, \lim_{n \rightarrow \infty} \frac{\beta_n}{b_n} = 0.$$

Lemma 1.3 (Hu, 2005, Lemma 1.2) [3] Let b_1, b_2, \dots be a non-decreasing unbounded sequence of positive numbers and a_1, a_2, \dots be nonnegative numbers. Let r and C be fixed positive numbers. Assume that for each $n \geq 1$,

$$E\left(\max_{1 \leq l \leq n} |S_l|\right)^r \leq C \sum_{l=1}^n \alpha_l, \quad (7)$$

$$\sum_{l=1}^n \frac{\alpha_l}{b_l^r} < \infty, \quad (8)$$

then (5) and (6) hold.

Lemma 1.4 (Yang, 2000, Corollary 3, Yang, 2001; Shao, 2000)[4][6][7] Let X_1, X_2, \dots be negatively associated random variables with zero means and $E|X_j|^r < \infty$, where

$r > 1$. Then there exists a positive constant C , which does not depend on n , such that

$$E(\max_{1 \leq k \leq n} |S_k|^r) \leq C \sum_{j=1}^n E|X_j|^r, \quad 1 < r \leq 2,$$

$$E(\max_{1 \leq k \leq n} |S_k|^r) \leq C[\sum_{j=1}^n E|X_j|^r + (\sum_{j=1}^n EX_j^2)^{r/2}], \quad r > 2.$$

In this paper, we assume that C, C_1, \dots are some positive constants (not necessarily always the same) independent of n .

II. MAIN RESULTS

Theorem 2.1 Assume that $\{X_n, n \geq 1\}$ be a Lacunary System, exists a positive constant K_p and $p > 2$, such that $\sup_j E|X_j|^p < \infty$, then for every $\delta > 0$,

$$\lim_{n \rightarrow \infty} \frac{S_n}{\sqrt{n}(\log n)^{1/p}(\log \log n)^{(1+\delta)/p}} = 0, a.s. \quad (9)$$

and for

$$b_n = \sqrt{n}(\log n)^{1/p}(\log \log n)^{(1+\delta)/p}, \quad n \geq n_0,$$

$$\alpha_n = K_p n^{p/2} - K_p(n-1)^{p/2},$$

$$\beta_n = \max_{1 \leq k \leq n} b_k v_k^{\delta/p}, \quad 0 < \delta < 1,$$

$$\frac{S_n}{b_n} = O\left(\frac{\beta_n}{b_n}\right) a.s., \quad \lim_{n \rightarrow \infty} \frac{\beta_n}{b_n} = 0. \quad (10)$$

Proof From Definition 1.3, for any sequence of real constant $\{C_i\}$,

$$E\left(\sum_{i=b+1}^{b+n} C_i X_i\right)^p \leq K_p \left(\sum_{i=b+1}^{b+n} C_i^2\right)^{p/2},$$

in particular where $C_i \equiv 1$, we have

$$E\left(\sum_{i=b+1}^{b+n} C_i X_i\right)^p = E|S_{b,n}|^p \leq K_p n^{p/2},$$

In Definition 1.1 take

$$g_n = g(b, n) = K_p^{2/p} n, \quad \alpha = \frac{p}{2},$$

then

$$g(b, k) = K_p^{2/p} k, \quad g(b+k, l) = K_p^{2/p} l$$

$$g(b, k) + g(b+k, l) = K_p^{2/p} (k+l) \leq g(b, k+l),$$

$$E|S_{b,n}|^p \leq K_p n^{p/2} = g^{p/2}(b, n), \quad n \geq 1, \quad p > 2,$$

we know that $\{X_n, n \geq 1\}$ has the p th moment function of supersensitive structure, and

$$\begin{aligned} \sum_{n=n_0}^{\infty} \frac{g_n^{p/2} - g_{n-1}^{p/2}}{b_n^p} &= \sum_{n=n_0}^{\infty} \frac{K_p(n^{p/2} - (n-1)^{p/2})}{n^{p/2}(\log n)(\log \log n)^{1+\delta}} \\ &\leq C \sum_{n=n_0}^{\infty} \frac{1}{n(\log n)(\log \log n)^{1+\delta}} < \infty, \end{aligned}$$

thus (9) follows from Lemma 1.2.

We assume that $\alpha_n > 0$ for infinitely many n . By (8) and Lemma 1.3, we know that

$$\sum_{n=1}^{\infty} \frac{\alpha_n}{b_n^r v_n^{\delta}} < \infty,$$

it is easy to see that $0 < \beta_k \leq \beta_{k+1}$ for $k \geq 1$, and

$$\sum_{n=1}^{\infty} \frac{\alpha_n}{\beta_n^r} \leq \sum_{n=1}^{\infty} \frac{\alpha_n}{\beta_n^r v_n^{\delta}} < \infty,$$

$$\begin{aligned} \frac{\beta_k}{b_k} &\leq \frac{\max_{1 \leq l \leq k_1} b_l v_l^{\delta/r}}{b_k} + \frac{\max_{k_1 \leq l \leq k} b_l v_l^{\delta/r}}{b_k} \\ &\leq \frac{\max_{1 \leq l \leq k_1} b_l v_l^{\delta/r}}{b_k} + v_{k_1}^{\delta/r}, \end{aligned}$$

from (8) and

$$\lim_{n \rightarrow \infty} b_n = \infty,$$

we get

$$\lim_{n \rightarrow \infty} \frac{\beta_n}{b_n} = 0.$$

Eq.(7) and Theorem 1.1 of Fazekas and Klesov (2000) [1] imply that

$$E\left(\max_{1 \leq l \leq n} \left|\frac{S_l}{\beta_l}\right|\right)^r \leq 4C \sum_{l=1}^n \frac{\alpha_l}{\beta_l^r} \leq 4C \sum_{l=1}^{\infty} \frac{\alpha_l}{\beta_l^r} < \infty,$$

hence by monotone convergence theorem, we have

$$E\left(\sup_{n \geq 1} \left|\frac{S_n}{\beta_n}\right|\right)^r = \lim_{n \rightarrow \infty} E\left(\max_{1 \leq l \leq n} \left|\frac{S_l}{\beta_l}\right|\right)^r \leq 4C \sum_{n=1}^{\infty} \frac{\alpha_n}{\beta_n^r} < \infty,$$

so that

$$\sup_{n \geq 1} \left|\frac{S_n}{\beta_n}\right| < \infty, a.s.,$$

and

$$0 \leq \left|\frac{S_n}{\beta_n}\right| \leq \frac{\beta_n}{b_n} \sup_{n \geq 1} \left|\frac{S_n}{\beta_n}\right| = O\left(\frac{\beta_n}{b_n}\right), a.s.,$$

this completes the proof.

Remark 1: Theorem 2.1 improve result of Ryozyo, Y. (Corollary 2) [8] and from strictly stationary strong mixing sequence to S_p system.

Theorem 2.2 Let (X_n, F_n) be a Locally Generalized Gaussian sequence, if $\sup_n \{X_n\} = k < \infty$, then for any $r \geq 2$

$$E\left|\sum_{i=a+1}^{a+n} C_i X_i\right|^r \leq K_r \left(\sum_{i=a+1}^{a+n} C_i^2\right)^{r/2} \quad (11)$$

furthermore, (9) and (10) hold.

Proof Let $A_n = \sum_{i=a+1}^{a+n} C_i^2$, $u = x/k^2 A_n$, by lemma 1 in [5], then

$$E(\exp(u \sum_{i=a+1}^{a+n} C_i X_i)) = E(\exp(u S_n)) \leq \exp(u^2 k^2 A_n / 2)$$

where

$$S_n = \sum_{i=a+1}^{a+n} C_i X_i, \quad \text{for } r \geq 2,$$

by Chebyshev's inequality, we get

$$\begin{aligned} E\left|\sum_{i=a+1}^{a+n} C_i X_i\right|^r &= r \int_0^\infty x^{r-1} P(|S_n| > x) dx \\ &\leq 2r \int_0^\infty x^{r-1} \exp(-x^2/2k^2 A_n) dx \\ &= 2^{r/2} r k^r A_n^{r/2} \int_0^\infty x^{r/2-1} \exp(-x) dx \\ &= K_r \left(\sum_{i=a+1}^{a+n} C_i^2\right)^{r/2} \end{aligned}$$

where $K_r = 2^{r/2} r k^r \int_0^\infty x^{r/2-1} \exp(-x) dx$,

Therefore, Locally Generalized Gaussian sequence is a Lacunary system, by Theorem 2.1, (9) and (10) hold.

Theorem 2.3 Let $\{X_n, n \geq 1\}$ be a NA sequence, satisfying $\sup_n |X_n|^p < \infty$, then for any $0 < p < 2, \alpha p \geq 1, p/2 < \delta \leq 1, x > 0$,

$$\sum_{n=1}^\infty n^{\alpha p - (1+\delta)} P\{|S_n| \geq x n^\alpha\} < \infty, \quad (12)$$

where $S_n = \sum_{i=1}^n X_i$.

Proof From lemma 1.3, when $C_i \equiv 1$, we have

$$E\left|\sum_{i=a+1}^{a+n} X_i\right|^p \leq K_p n^{p/2},$$

By Markov's inequality we get

$$\begin{aligned} \sum_{n=1}^\infty n^{\alpha p - (1+\delta)} P\{|S_n| \geq x n^\alpha\} &\leq \sum_{n=1}^\infty \frac{n^{\alpha p - 1 - \delta} E|S_n|^p}{x^p n^{\alpha p}} \\ &\leq K_p x^{-p} \sum_{n=1}^\infty \frac{n^{\alpha p - 1 - \delta} n^{p/2}}{n^{\alpha p}} \\ &= K_p x^{-p} \sum_{n=1}^\infty \frac{1}{n^{1+(\delta-p/2)}} < \infty. \end{aligned}$$

Theorem 2.4 Let $\{X_n, n \geq 1\}$ be a m_0 dependent sequence with zero mean, if $\sup_n |X_n|^r < \infty$, then for any $1 \leq r < 2$,

$$\frac{S_n}{n^{1/r}} \rightarrow 0 (n \rightarrow \infty), a.s., \quad (13)$$

where $S_n = \sum_{i=1}^n X_i$.

Proof for every $t = 0, 1, \dots, m_0 - 1, \{X_{t+m_0k}, k = 1, 2, \dots\}$ be a independent sequence, and

$$\sum_{j=m}^n C_j X_j = \sum_{t=0}^{m_0-1} \sum_{k=0}^{n_0} C_{m+t+m_0k} X_{m+t+m_0k},$$

by C_r inequality, we get

$$E\left(\left|\sum_{j=m}^n C_j X_j\right|\right)^2 \leq m_0 \sum_{t=0}^{m_0-1} E\left(\sum_{k=0}^{n_0} C_{m+t+m_0k} X_{m+t+m_0k}\right)^2$$

$$= m_0 \sum_{t=0}^{m_0-1} \sum_{k=0}^{n_0} C_{m+t+m_0k}^2 E X_{m+t+m_0k}^2$$

$$= m_0 \sum_{j=m}^n C_j^2 E X_j^2 \leq k m_0 \sum_{j=m}^n C_j^2,$$

$\{X_n, n \geq 1\}$ be a S_2 system, by Jensen's inequality, for $1 \leq r < 2$,

$$E\left(\left|\sum_{j=m}^n C_j X_j\right|\right)^r \leq C \left(\sum_{j=m}^n C_j^2\right)^{r/2},$$

in particular, when $C_j \equiv 1$, we obtained

$$E|S_n|^r \leq C n^{r/2}.$$

In Definition 1.1 take

$$g_n = g(b, n) = K^{2/r} n, \quad \alpha = \frac{r}{2}, \quad b_n = n^{1/r},$$

then

$$g(b, k) = K^{2/r} k, \quad g(b+k, l) = K^{2/r} l$$

$$g(b, k) + g(b+k, l) = K^{2/r} (k+l) \leq g(b, k+l),$$

$$E|S_{b,n}|^r \leq K n^{r/2} = g^{r/2}(b, n), \quad n \geq 1, \quad 1 \leq r < 2,$$

we know that $\{X_n, n \geq 1\}$ has the p th moment function of superadditive structure, and

$$\begin{aligned} \sum_{n=1}^\infty \frac{g_n^{r/2} - g_{n-1}^{r/2}}{b_n^r} &= \sum_{n=1}^\infty \frac{K(n^{r/2} - (n-1)^{r/2})}{n} \\ &\leq C \sum_{n=1}^\infty \frac{n^{r/2-1}}{n} = C \sum_{n=1}^\infty \frac{1}{n^{2-r/2}} < \infty, \end{aligned}$$

thus (13) follows from Lemma 1.2.

Remark 2 This result extends independent and identically distributed Marcinkiewicz Law of large numbers for m_0 -dependent sequences.

ACKNOWLEDGMENT

This work was supported by the Project Ministry of Education of PR China (10YJC630143) and the science Foundation of the Anhui Province (KJ2010B001, 2010sk226, 2011sk162).

REFERENCES

- [1] Fazekas, I., Klesov, O., 2000. *A general approach to the strong law of large numbers*. Theory Probab. Appl. 45, 436-449.
- [2] Fikhtengolts, G.M., 1954. *A Course of Differential and Integral Calculus*. People's Education Press, Beijing (in Chinese).
- [3] Hu Shuhe, 2005. *A general approach rate to the strong law of large numbers*. Statistics & Probability Letters 76, 843-851.
- [4] Shao, Q., 2000. *A comparison theorem on maximal inequalities between negatively associated and independent random variables*. J. Theoret. Probab. 13 (2), 343-356.
- [5] Shao, Q., Yu, H., 1996. Weak convergence for weighed empirical processes of dependent sequences. Ann. Probab. 24, 2098-2127.
- [6] Yang, S., 2000. *Moment inequalities for partial sums of random variables*. Sci. China (series A, Chinese) 30 (3), 218-223.
- [7] Yang, S., 2001. *Moment inequalities for partial sums of random variables*. Sci. China (series A, English) 44, 1-6.
- [8] Ryozyo, Y., 1980. *Moment Bounds for Stationary Mixing Sequences*. Z. W. verw. Gebiete 52, 45-57.