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Synchronisation of alpha-stable levy noise-based Random Communication System

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Abstract: In this study, the pilot-assisted synchronisation method for a random communication system (RCS) has been proposed. The pilot symbol, which has alpha-stable distribution, has been used to establish synchronisation and to maintain covertness in the RCS. The introduced synchronisation block (SB) consists of fractional lower-order covariance-based correlators (FLOCCs), threshold detectors (TDs) and the synchronisation control block. To measure the performance of the proposed SB, the performance criterion, i.e. confidence ratio (CR), has been proposed. The reliability of the proposed SB can be enhanced by altering the CR and the achieved CR by using the FLOCCs and TDs in SB.

1 Introduction

Synchronisation is a vital step in designing any wire-line or wireless communication system (CS). Especially, in wireless CSs, synchronisation is very important due to the presence of much intense channel impairments, e.g. noise, fading, interference, distortion and attenuation. The pilot-assisted transmission (PAT) is a method in which a transmitter and receiver communicate through known information bearing signals, i.e. pilot symbols (PSs), to overcome the channel impairments by exploiting channel estimation, receiver adaptation and optimal decoding. The concept of PA synchronisation (PAS) through PAT was first introduced by Cavers in [1] as PS-assisted modulation. Some of the other approaches on PAT were focused on fast-varying channels [2]. Currently, PAT is an essential element in modern wireless CSs, for instance, the global system for mobile communication system uses 26 bits PSs and the time-division multiple access standard includes PSs at the beginning of each packet [2]. Wideband code-division multiple access (CDMA) and CDMA-2000 are third generation wireless CSs which send PSs with information signals simultaneously. Fourth generation broadband systems such as HyperLAN II and IEEE 802.11 family also use PSs for communication [2].

Also in the conventional spread spectrum (SS) CSs, synchronisation is achieved between transmitter and receiver through PSs known as pseudo-noise (PN) codes [3–5]. The method to synchronise chaotic CSs by PN sequences for the PAS was proposed by Jovic *et al.* [6]. The advantage of using PN sequences as PSs is a good correlation but it lacks security [7]. Therefore, in order to improve the security of the chaotic CSs the PAS approach using gold sequences, i.e. shifted PN sequences, as PSs were introduced [8]. However, the PAS method based on a chaotic pilot in [9] has improved the security by achieving complete masking, since all transmitted signals are chaotic which has further strengthened the concept of PAS in covert CSs.

Similarly, in molecular communication (MC), i.e. a biologically inspired form of communication, where chemical signals are used to transfer information, synchronisation is also vital to build diffusion-based MC systems [10]. Most studies on MC systems have assumed perfect synchronisation while recent researches focused on synchronisation of MC systems. The studies in [11–15] have presented to achieve the PAS by using specific molecule types as PSs. In [11], two genes, i.e. luxI and luxR, are used as PSs in synthetic gene regulatory network. Similarly in [12, 13], the method of biological bacterial Quorum sensing has been introduced in which the bacteria of different species are used as PSs for synchronisation between the nodes of a nanonetwork. Additionally, in [14, 15], the PAS method for the molecular machine, i.e. a device with a size in the nano to micro-scale range, has been introduced where the pulses of inhibitory molecules, i.e. negative autoregulating molecules, are used as PSs. So, the PAS has been used in manmade CSs as well as in the CSs of nature.

A new branch of SS-based covert communication known as random CS (RCS) has evolved recently. RCS uses the stochastic process as a carrier to send binary messages, and hence can be considered more secure as compared with conventional CSs. The stochastic process shift keying-based RCS was first introduced by Salberg *et al.* where they used autoregressive/moving average processes to transmit binary messages [16]. However, after almost 15 years, Cek *et al.* introduced RCS in which symmetric alpha-stable (SαS) and skewed α-stable noises are random carriers which are information bearing signals [17, 18]. Different receiver designs for SαS and skewed α-stable noise-based RCSs were also introduced to increase the bit error rate (BER) performance [19–21]. Also, a new model of RCS based on joint normal distribution has been introduced by Xu *et al.* in [22]. Similarly, the security performance trade-off characteristics have been introduced recently by Ahmed and Savaci in [23] to measure the security of RCSs. The effects of imperfect synchronisation in RCSs have already been observed in [24]. Therefore, all RCS studies mentioned above assume perfect synchronisation. However, the method to achieve the synchronisation in RCSs has not been introduced.

To fulfil the gap of synchronisation issue in RCSs, in this paper, we have newly developed the concept of PAS for RCSs. The proposed idea is inspired by the application of PAT and PAS in both manmade and natural CSs discussed above. The proposed PAS method is based on the utilisation of α-stable noise as the pilot sequence sampled from a α-stable distribution. This pilot sequence is different from the random carriers which have been obtained from the α-stable distributions in the transmitter. The utilisation of α-stable noise as the pilot sequence ensures secrecy during synchronisation interval which is the main objective of RCSs. Since, the second-order and higher-order moments of α-stable random variable do not exist, all existing time-delay estimation methods, i.e. correlation and covariance, which are based on second-order statistics cannot be applied for the synchronisation of RCS. Therefore, the fractional lower-order covariance-based correlator (FLOCC) has been used as the new measure of similarity between two α-stable distributions [25]. Hence, the synchronisation block (SB) consisting of FLOCCs and multiple threshold detectors (TDs) have been proposed for the receiver side to predict the exact accepting time of the data. Also, the criterion known as confidence

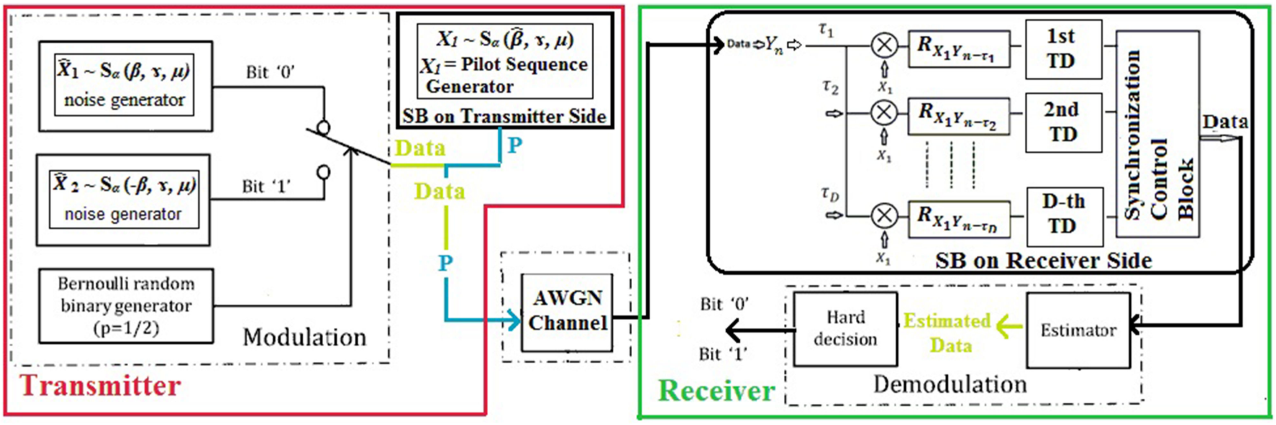

Fig. 1 *Block diagram of the RCS based on α-stable Levy noise along with the proposed SBs on transmitter and receiver sides*

ratio (CR) to measure the reliability of the proposed SB has also been proposed. In Section 2, α-stable distributions and noise shift keying method in [23] are briefly given. In Section 3, the proposed synchronisation method based on the pilot sequence which is also obtained from α-stable distributions are presented. The simulations given in Section 4 have proved the achievement of the proposed SB.

2 *α*-Stable noise-based RCS

The proposed PAS method is based on α-stable distribution.

2.1 α-Stable distribution [26]

$S_\alpha(\beta, \gamma, \mu)$ denotes the α-stable distribution where the parameters are defined as: the characteristic exponent $\alpha(0 < \alpha \le 2)$, the skewness parameter $\beta(-1 \le \beta \le 1)$, (the dispersion parameter γ $(\gamma \ge 0)$ and the location parameter $\mu \in R$.

The characteristic function of α-stable noise $X–S_\alpha(\beta, \gamma, \mu)$ is expressed as

$$(\theta) = \begin{cases} \exp\left\{ j\mu\theta - \gamma^\alpha |\theta|^\alpha \left(1 - j\beta\, \mathrm{sign}(\theta) \tan\left(\dfrac{\alpha\pi}{2}\right)\right)\right\} \\ \qquad\qquad \text{if } \alpha \ne 1 \\ \exp\left\{ j\mu\theta - \gamma|\theta| \left(1 + j\beta \dfrac{2}{\pi} \mathrm{sign}(\theta) \ln\left(\dfrac{\alpha\pi}{2}\right)\right)\right\} \\ \qquad\qquad \text{if } \alpha = 1 \end{cases} \tag{1}$$

Remark 1: Gaussian, Cauchy and Levy Distributions are special α-stable distributions defined as $X–S_{\alpha=2}(\beta = 0, \gamma, \mu)$, $X–S_{\alpha=1}(\beta = 0, \gamma, \mu)$ and $X–S_{\alpha=0.5}(\beta = 1, \gamma, \mu)$.

If $\alpha < 2$, the α-stable distribution does not have second- or higher-order moments; moreover, if $\alpha \le 1$, the first-order moment does not also exist [26]. The pilot sequence which has α-stable distribution has been generated by the method given in [27].

2.2 α-Stable noise shift keying

The random carriers $\hat{X}_1$ and $\hat{X}_2$ in the transmitter, as shown in Fig. 1, are obtained from the antipodal skewed α-stable distributions, i.e. $\hat{X}_1 – S_\alpha(-\beta, \gamma, \mu)$ and $\hat{X}_2 – S_\alpha(\beta, \gamma, \mu)$. By choosing the slant parameter β as '0' or '1', the corresponding distributions or the random carriers are skewed either to the right or to the left. The receiver estimates corresponding β by the maximum extreme value method in [23].

Since, the receiver does not know the exact time instant of accepting the data samples, therefore, the synchronisation between the transmitter and receiver should be achieved. In the sequel, the new synchronisation method has been proposed.

3 Synchronisation

For synchronisation, first, the pilot sequence pre-known both by the transmitter and the intended receiver is produced in the 'SB on the transmitter side'. Then, the cut-off threshold value based on the FLOC of the PSs is pre-determined, which is also pre-known both by the transmitter and the intended receiver. The number of FLOCCs and the number of TDs in the 'SB on the receiver side' is also pre-decided both by the transmitter and the intended receiver.

3.1 SB on the transmitter side

The proposed SB which has been embedded in RCS has been shown in Fig. 1. The PS X_1 in SB is also obtained from another α-stable distribution, i.e. $X_1 – S_\alpha(\hat{\beta}, \gamma, \mu)$,, where $\hat{\beta} \ne \beta$.

3.1.1 Construction of the PS and pilot sequence: PS X_1 which is sent 'm' consecutive times to construct the pilot sequence P_1 is described as

$$P_1 = [X_1, X_1, \ldots, X_1]_{1 \times mN} \tag{2}$$

where $X_1 = [x_1\ x_2\ \ldots\ x_N]_{1 \times N}$ and 'N' represents the number of α-stable noise samples per PS. Every nth PS 'X_n' is constructed from the elements of X_1 defined below as:

$$X_n = [x_n\ \ldots\ x_{N-1+n}]_{1 \times N} \tag{3}$$

for $n = 1, 2, \ldots, (m-1)N + 1$ and

$$x_n = x_{uN+n} \tag{4}$$

for $u = 0, 1, 2, \ldots, m-1$.

Hence, the nth pilot sequence P_n is defined as

$$P_n = [X_n, X_n, \ldots, X_n]_{1 \times mN} \tag{5}$$

3.1.2 Fractional lower-order covariance for the PSs: The FLOC vector '$\boldsymbol{R}$' consists of the FLOCs $R_{X_1X_k}$ of the PS X_1 with the PSs X_k which has been obtained as

$$\boldsymbol{R} = [R_{X_1X_2}\ R_{X_1X_3} \ldots R_{X_1X_k} \ldots R_{X_1X_{N+1}}]_{1 \times N} \tag{6}$$

where the FLOC $R_{X_1X_k}$ is estimated as in [25]

$$R_{X_1X_k} = \frac{\sum_{n=N_1+1}^{N_2} |x_1[n]|^a \cdot |x_k[n]|^b\, \mathrm{sign}(x_1[n] \cdot x_k[n])}{N_2 - N_1} \tag{7}$$

for $k = 2 \ldots N + 1$ where $N_1 = 0$, $N_2 = N$ and the fractional powers are $a = b = \alpha/2$ and

$$\mathrm{sign}(x) = \begin{cases} -1 & \text{if } x < 1 \\ 0 & \text{if } x = 0 \\ 1 & \text{if } x > 1. \end{cases} \tag{8}$$

Note that FLOCs between the nth PS X_n and the jth PS X_j satisfies the following relation:

$$R_{X_n X_j} = R_{X_n X_{(uN+j)}} \tag{9}$$

for $u = 0, 1, \ldots, m-1$ and $j = n+1, \ldots, N+n$.

If we assume that the additive channel noise is Gaussian, then the noisy PSs X'_n are assumed as

$$X'_n = X_n + G \quad \text{and} \quad G - S_{\alpha=2}(\beta, \gamma, \mu) \tag{10}$$

then the new FLOC vector '$\boldsymbol{R}_G$' can be constructed as

$$\boldsymbol{R}_G = [R_{X'_1 X'_2} \; R_{X'_1 X'_3} \ldots R_{X'_k} \ldots \; R_{X'_1 X'_{N+1}}]_{1 \times N} \tag{11}$$

Remark 2: FLOC is a robust time-delay estimation method that performs well not only for the Gaussian noise environments but also in the presence of impulsive noise, i.e. α can be of any value within its admissible range (0, 2], which has been proved in [25].

3.1.3 Cut-off threshold (L_{th})*:* The cut-off threshold has been predetermined as

$$L_{\mathrm{th}} = \frac{\|\boldsymbol{R}\|_\infty + \|\boldsymbol{R}_{\mathrm{red}}\|_\infty}{2} \tag{12}$$

where $\|R\|_\infty = \max_{1 \le i \le N}|r_i| = |r_L|$ and $\boldsymbol{R}_{\mathrm{red}}$ is the reduced vector obtained by deleting r_L from R.

This L_{th} is pre-known both by the transmitter and the intended receiver which is used for hard decision in the threshold detection process.

The idea of choosing L_{th} as in (12) is that $\|R\|_\infty$ gives the highest FLOC value for $R_{X_1 X_k}$ which is required as a threshold to the receiver for identification of the PS X_1. However, $\|R_{\mathrm{red}}\|_\infty$ gives the highest FLOC value for $R_{X_1 X_k}$ which is required as a threshold to the receiver for identification of all other PSs, except X_1. Hence, the computed mid-value, i.e. L_{th}, between $\|R\|_\infty$ and $\|R_{\mathrm{red}}\|_\infty$ is found to be the best criterion for accurate detection of X_1 on the receiver side.

3.2 SB on the receiver side

The SB on the receiver side, as shown in Fig. 1, consists of total 'D' FLOCCs, TDs and the synchronisation control block (SCB) for the pilot sequence tracking and acquisition. The choice of 'D' is arbitrary which has been used to measure the reliability of the SB from newly introduced criterion known as 'CR', explained in the following section.

3.2.1 FLOCCs and TDs: The SB receives the pilot sequence 'Y_n' as

$$Y_n = P_n + N_{\mathrm{channel}} \tag{13}$$

Since, it is transmitted through additive white Gaussian noise (AWGN) channel and N_{channel} is the actual channel noise added to the transmitted pilot sequence P_n which is defined below as:

$$N_{\mathrm{channel}} - S_2(0, \gamma_{N_{\mathrm{channel}}} = 1, 0) \tag{14}$$

Note that in Y_n, the noisy sample data is different than X'_n because N_{channel} is not known a priori while G in the transmitter side has been predicted as a channel noise a priori.

The dth FLOCC starts taking samples of Y_n after a delay of 'τ_{d}' seconds where 'τ_{d}' is the respective delay for accepting the first sample for the dth correlator

$$\tau_{\mathrm{d}} = \frac{(d-1) \times T_{\mathrm{sample}}}{D} \quad (1 \le d \le D) \tag{15}$$

and T_{sample} is the duration between two consecutive noise samples.

Over detection, i.e. detection of one sample multiple times by a single TD during the T_{sample} duration, can be avoided by the proper selection of τ_{d}'s with the following criterion:

$$\tau_{\mathrm{D}} < T_{\mathrm{sample}} \tag{16}$$

Some initial samples might be missed by the SB because of the random delay arising from the channel impairments such as fading, multipath propagation etc. Therefore, the first received signal to SB might not be Y_1 and every FLOCC starts correlating the N received samples with first PS 'X_1' from the time instant of reception. The FLOC procedure will then be repeated every T_{sample} seconds to look up for the required threshold level, i.e. L_{th}. The first threshold will be achieved when the threshold value from FLOC $R_{X_1 Y_{N+1}}$ will be obtained. The threshold can be achieved on more than one TD which will help the SCB to register it as first PS acquisition.

3.2.2 Synchronisation CB: We have arbitrarily chosen the number of PSs 'm' and a total number of FLOCCs 'D' equal to three and number of α-stable noise samples 'N' equals to 500. In the flow diagram of SB, only $m-1$ PSs are identified and for the chosen values of 'm', 'N' and 'D' only two PSs, i.e. $m-1$, are identified as shown in Fig. 2. It illustrates the steps from noisy pilot samples reception and predicting the time instant of accepting the data samples and the following definitions will clarify Fig. 2.

Performance measure of the pilot sequence: To measure the performance of any pilot sequence, which is used to synchronise the RCSs, the following definitions are given below.

Required CR (RCR)

$$\mathrm{RCR} \doteq \frac{D_{\mathrm{req}}}{D} \tag{17}$$

where 'D_{req}' is the required number of TDs that should achieve the required threshold, i.e. L_{th}, to claim PS acquisition and D_{req} is selected by the transmitter and the intended receiver.

CR

$$\mathrm{CR} \doteq \frac{D_{\mathrm{ach}}}{D} \tag{18}$$

where D_{ach} is the number of TDs that have achieved the required threshold, i.e. L_{th}..

PS acquisition: The first PS acquisition, i.e. S^1_{acq}, is obtained at the FLOC $R_{X_1 Y_{N+1}}$ with the condition $D_{\mathrm{ach}} = \mathrm{D}_{\mathrm{req}}$.

PS tracking interval: The qth PS tracking interval, i.e. T^q_{tr}, continues until the time instant of the qth PS acquisition (i.e. S^q_{acq}) which is obtained at the FLOC $R_{X_1 Y_{qN+1}}$ with the condition $D_{\mathrm{ach}} = D_{\mathrm{req}}$.

The time instant for the qth PS acquisition is defined below as:

$$S^q_{\mathrm{acq}} = \sum_{k=1}^{q} T^k_{\mathrm{tr}} \tag{19}$$

for $q = 1, \ldots, m-1$.

Data acceptance time (DAT): The DAT tells the exact time instant, i.e. T_{data}, to start acceptance of the data after synchronisation as

$$T_{\mathrm{data}} = S^{m-1}_{\mathrm{acq}} + T_{\mathrm{psy}} \tag{20}$$

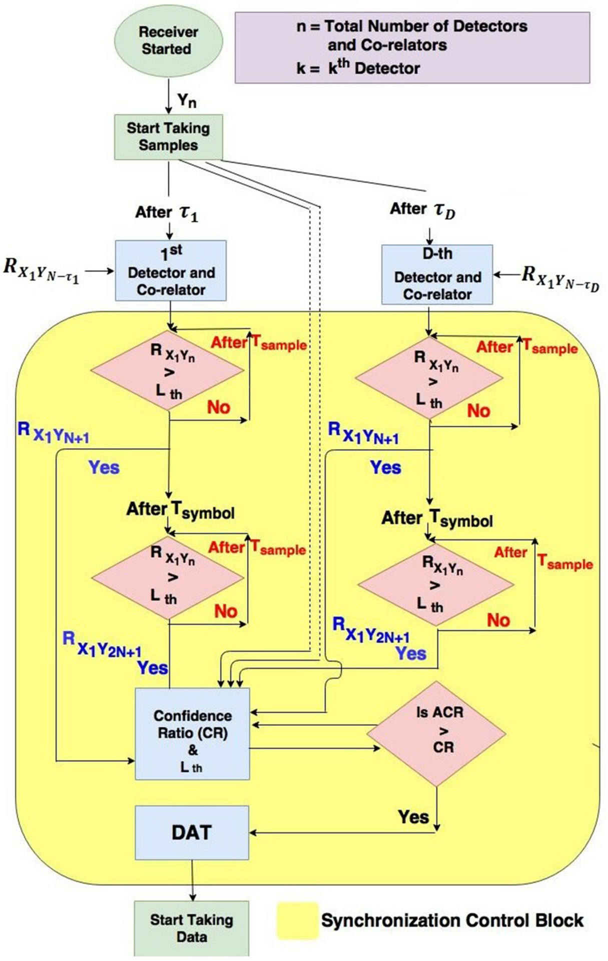

Fig. 2 *Flow diagram of the SB on receiver side*

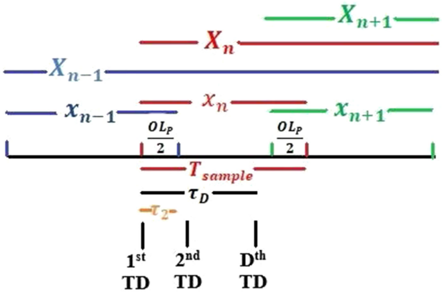

Fig. 3 *Overlapped sample* x_n *of the PS* X_n

where T_{psy} is the duration of the PS.

Hence, the total duration required to establish synchronisation, i.e. T_{sync}, in RCS by the proposed method can be found as

$$T_{\text{sync}} = T_{\text{pro}} + T_{\text{data}} \tag{21}$$

where 'T_{pro}' is the signal propagation time from transmitter to receiver.

3.3 Overlapping margin (OL_M)

The received PSs may be partially overlapped with each other. Assuming that we have a specific percentage of overlapping between the noise samples of every PS denoted by 'OL_P' in the range $0 \le \text{OL}_\text{P} \le 1$ then every noise sample x_n of the PS X_n will be overlapped with x_{n-1} and x_{n+1} for the first and last '$\mathbf{OL}_\text{P}/2 \times T_{\text{sample}}$' interval, respectively, as shown in Fig. 3. The overlapping margin, i.e. OL_M, in the range $0 \le \text{OL}_\text{M} \le 1$, is the maximum percentage of overlapping, i.e. OL_P, which can be resisted by the proposed synchronisation method for fixed 'D' and 'τ_D' which is defined below as:

$$\text{OL}_\text{M} < \frac{T_{\text{sample}} - \tau_\text{D}}{T_{\text{sample}}} \tag{22}$$

If OL_P is below OL_M for fixed 'D', 'τ_D' and 'T_{sample}' and τ_D is taken according to the criterion given in (15), then at least '$D-1$' FLOCCs and TDs will be able to detect the sample correctly from the non-overlapping region of every noise sample x_n of the PS X_n which is also shown in Fig. 3. However, OL_M decreases with the increment in 'D' and a trade-off has to be maintained for this purpose. The utilised values of '$D=3$' give the leverage of overlapping margin up to 33%, i.e. $\text{OL}_\text{M} = 0.33$.

3.4 Performance measure of the RCS under Gaussian noise channel

To evaluate the overall performance of the proposed RCS, BER versus mixed signal-to-noise ratio (MSNR) performance has been analysed, where MSNR or dispersion ratio is defined as in [25] while BER is the percentage of bits with errors divided by the total number of bits that have been transmitted

$$\text{MSNR}_{\text{dB}} = 10\log\frac{\gamma}{\gamma_{N_{\text{channel}}}} \tag{23}$$

where γ and $\gamma_{N_{\text{channel}}}$ are the dispersion parameters of the PS and the channel noise, respectively.

4 Simulation

The following simulations have been made for '$m = D = 3$' *and* '$N = 500$' as preselected parameters by the transmitter and the intended receiver.

T_{psy} is chosen as 1 s; therefore, the corresponding T_{sample} is equal to $1/500$ s. D_{req} is chosen as two and hence RCR in (16) is 66%. The skewness parameter $\hat{\beta}$ equals to 1 and location parameter μ equals to 0 have been used throughout this paper, whereas the characteristic exponent α equals to 1.6 and MSNR equals to −4 dB have been used to obtain Figs. 4–7.

4.1 Generation and FLOC of the PS and the pilot sequence

The pilot sequence P_1 and the noisy pilot sequence P'_1, i.e. $P_1 + G$, are shown at the top and bottom of Fig. 4, respectively. The total duration of P'_1 is 3 s since $T_{\text{psy}} = 1$ and $m = 3$.

The FLOC values ($R_{X_1X_k}$) between the PS X_1 and the PSs X_k of P_1 are shown. Similarly in Fig. 5*b*, the FLOC values ($R_{X'_1X'_k}$) between the noisy PS X'_1 and the PSs X'_k of P'_1 are shown.

The values of L_{th} of R and $\boldsymbol{R}_G$ are also shown in Figs. 5*a* and *b*, respectively.

4.2 Performance of the proposed PAS method and SB on receiver side

The performance of the proposed SB on the receiver side is shown in this section. The three sampled versions of the received signal Y_n for FLOCCs are shown in Fig. 6, which are obtained by the delay criteria in (15) and (16). As explained in Section 3.2.1, the first received signal to SB might not be Y_1, and hence Y_{260} has been chosen arbitrarily as the first received Y_n to the SB. Therefore, from the total duration of 3 s, i.e. $m \times N = 3 \times 500$ samples, of the pilot sequence, the first 0.5 s, i.e. ∼259 samples, are considered as not being received to the SB on receiver side, whereas the later 2.5 s, i.e. 1241 samples, is considered as being received for decoding and establishing synchronisation.

The outputs of TDs and L_{th} are shown in Figs. 7*a* and *b* the first PS interval T^1_{tr} ends at S^1_{acq} when outputs of TDs are bigger than L_{th}. According to Fig. 7*a*, the output of two TDs crossed the

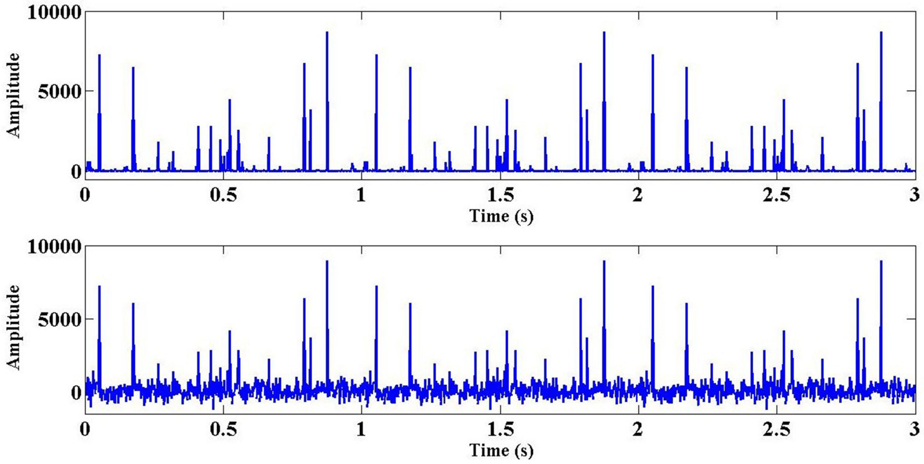

Fig. 4 *Pre-decided pilot sequences*
(a) Pilot sequence $\boldsymbol{P}_1$, ***(b)*** Noisy pilot sequence $\boldsymbol{P}'_1$

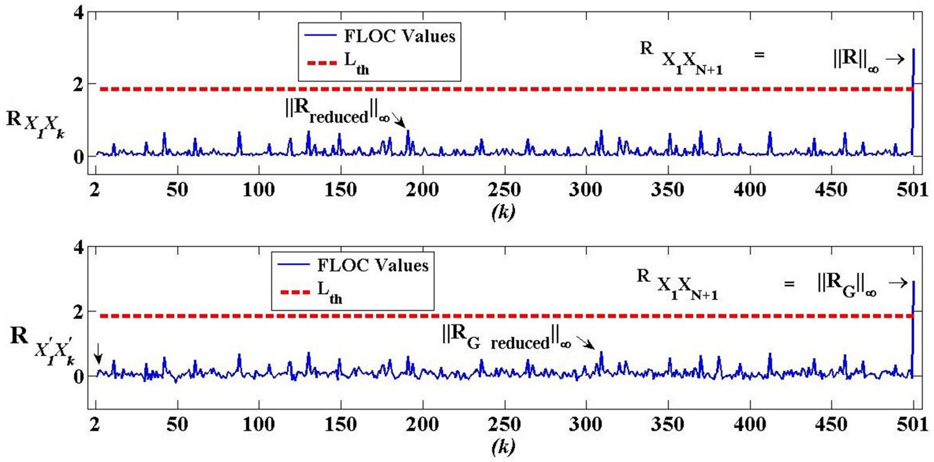

Fig. 5 *FLOC vectors '$\boldsymbol{R}$' and '$\boldsymbol{R}_G$'*
(a) FLOCs of $\boldsymbol{X}_1\boldsymbol{X}_k$, ***(b)*** FLOCs of $\boldsymbol{X}'_1\boldsymbol{X}'_k$

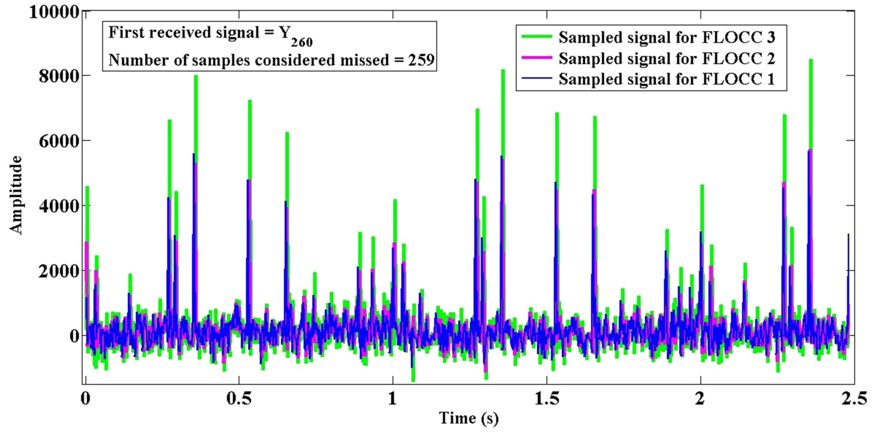

Fig. 6 *Output of SB on the receiver side*

L_{th} after ∼0.4 s, hence resulting in CR of 66%; therefore, it has been registered as first acquisition, i.e. $S_{\text{acq}}^1 = 0.4\,\text{s}$. Similarly, $S_{\text{acq}}^2 = 1.4\,\text{s}$ is made after $T_{\text{tr}}^2 = 1\,\text{s}$ and hence after two, i.e. $m - 1$ acquisitions, the DAT gives the exact time of data acceptation, i.e. $T_{\text{data}} = 2.4$ s, in (20).

The BER *versus* MSNR performance of the proposed system for various characteristic exponents has been shown in Fig. 8. The proposed system has shown efficient performance as it is capable to achieve the targeted BER of 10^{-3} even with increased characteristic exponents, i.e. decreased impulsiveness. Moreover, the BER at any specific MSNR can be improved further by decreasing the characteristic exponent.

4.3 Effects of number of FLOCCs and TDs on CR

The number of TDs and FLOCCs in SB affects the CR. The increase in the number of TDs and FLOCCs increases the CR as shown in Fig. 9. Hence, the confidence of the proposed synchronisation scheme increases. The criterion 'CR versus D' can be used to check the performance of any pilot sequence in establishing synchronisation in RCS in comparison with the proposed pilot sequence obtained from α-stable noise. Also, the

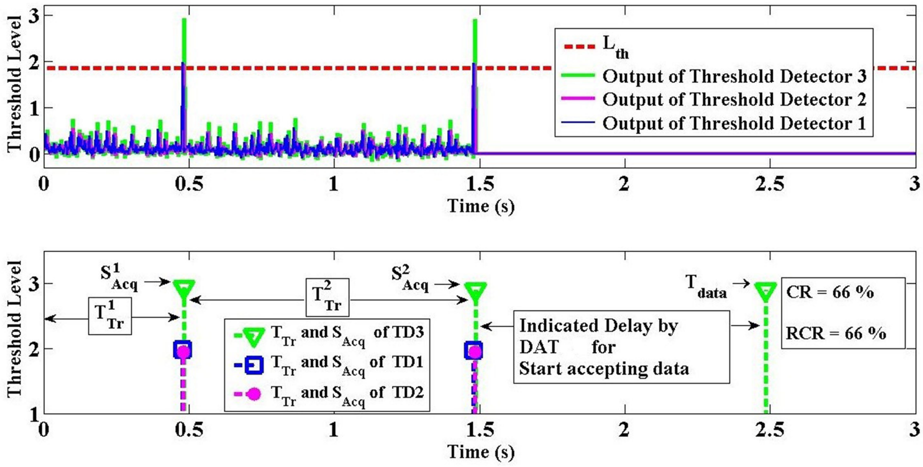

Fig. 7 *Skewness parameter*
(a) Output of TDs, ***(b)*** Output of SCB

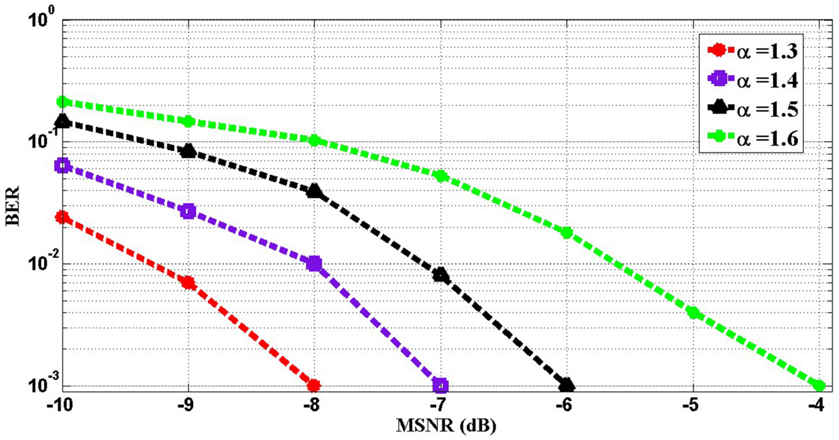

Fig. 8 *BER versus MSNR for different characteristic exponents 'α'*

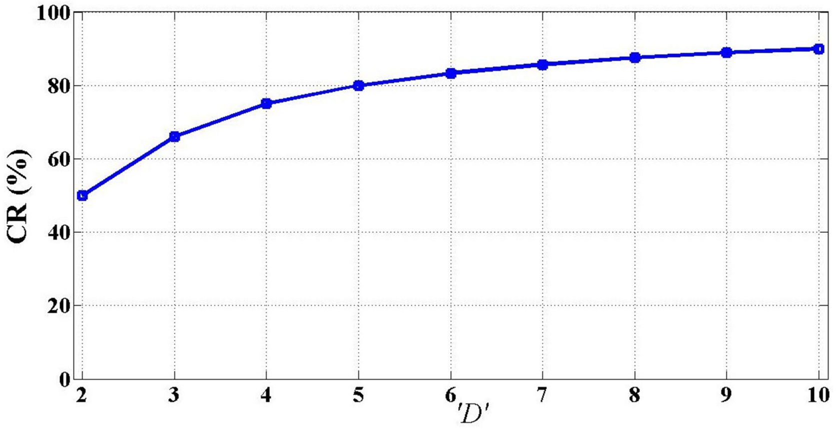

Fig. 9 *CR versus number of detectors and FLOCCs in SB (CR versus D)*

performance of the pilot sequences obtained from same or different noise distributions in different channels can also be analysed by the proposed method.

5 Conclusion

Since, the PSs have α-stable distributions with infinite variance; it keeps the layer of security in preventing intruders during the synchronisation interval. Also, the number of PSs in the pilot sequence and the number of TDs in the SB are chosen a priori, both by the transmitter and the intended receiver; therefore, these parameters, besides increasing the security level, also allow the users to adjust the RCS according to the channel impairments. Moreover, using different impulsiveness parameter, i.e. characteristic exponent 'α', and the skewness parameter, i.e. $\hat{\beta}$, might bring the capability to adjust the security of RCS for various channel conditions.

Owing to the utilisation of α-stable noise, which has infinite variance, both as a random carrier and as a PS, the proposed PAS method for RCS might; therefore, be more secure in comparison with different noise-based and chaotic PS-based synchronisation methods. The new criteria CR and RCR in SB can also be used to measure the performance of any PAS methods for SS-based CSs. These issues will be investigated as a future work.

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