Robust Phase Synchronization for STBC Coded MIMO Systems

Emna Ben Slimane
Communication Systems Laboratory,
National Engineering School of Tunis,
Tunisia
emna.benslimane@enig.rnu.tn

Slaheddine Jarboui
College of Computer Science,
King Khalid University,
Abha, KSA
slaheddine.jarboui@fss.rnu.tn

Ammar Bouallègue
Communication Systems Laboratory,
National Engineering School of Tunis,
Tunisia
ammar.bouallegue@enit.rnu.tn

***Abstract*— Multiple-Input Multiple-Output (MIMO) systems are very sensitive to carrier phase offset. In this paper, challenges regarding the provision of phase offset in orthogonal space time block codes (STBC) coded MIMO systems over Rayleigh fading channels are addressed. We develop a novel robust phase offsets estimation algorithm for MIMO systems based on STBC codes. Simulation results prove that the proposed phase offsets synchronizer provides accurate estimation.**

Keywords—STBC codes; MIMO scheme; Phase offset; blind estimation.

I. INTRODUCTION

In recent years, multiple antenna schemes have sparked wide interest and they are widely used in diverse communication systems due to their high spectral efficiency [1]. STBC coding has been well known as one powerful technique used in MIMO schemes to mitigate the impairments of wireless fading by exploiting both time and antenna diversity. These codes were extensively investigated. More specifically, STBC using coherent detection was proposed in [2, 3]; differential detection for STBC was proposed in [4, 5].

In the literature, some works in STBC coding assume perfect phase synchronization. Unfortunately, in practice, such an assumption is rarely valid in the presence of noise. Carrier phase recovery is surely crucial for MIMO schemes under STBC coding [6]. Indeed, the phase offset causes significant performance degradation. To circumvent this critical weakness, a phase synchronization technique can be applied in order to acquire the actual phase offset. Therefore, accurate and efficient phase estimation plays a key role in multiple antennas communication systems. Then, a proper estimation technique is needed to preserve the remarkable performance of MIMO schemes in presence of imperfect phase synchronization. In addressing the issue of phase synchronization, several algorithms have been introduced to estimate the phase offset and to study the Cramér–Rao lower bound (CRLB) in Single-Input Single-Output (SISO) systems [7]. However, these results are not directly applied to MIMO systems, where signals at each receive antenna are affected by a phase offset. Indeed, in these communications systems, the phase offset at each receive antenna consists of a multiplicative term that generates a rotation of the symbols and erroneous detection. In [8], studies of the effect of phase noise on the capacity of MIMO channels have shown that phase offsets may significantly limit the performance of these systems. Therefore, a phase synchronizer is required at the receive side.

Recently, phase estimation algorithm in multiple antenna systems are expanding. The authors in [9] proposed a joint supervised channel and phase noise estimation method for MIMO systems. Moreover, estimation techniques of phase offsets in MIMO system have been proposed with a perfect knowledge of the MIMO channel coefficients in many researches [10]-[11]. In this context, an algorithm based on the EM (Expectation Maximization) algorithm was applied [10] for the signal detection in the presence of phase noise. In addition, the authors in [11] have considered a Wiener filter approach to estimate the parameters of phase noise in MIMO systems. Assuming a perfect parameter estimation of the MIMO channel, a semi-blind frequency synchronization algorithm [12] has been established for the STBC-OFDM (Orthogonal Frequency Division Multiplexing) systems. The purpose of our recent work in [6] was to compensate the phase offsets in multiple antenna systems by using an efficient differential detection [5] without any channel state information (CSI).

To achieve accurate synchronization in MIMO systems without any resort neither to long pilot-symbol sequence [2] nor to complex differential mechanisms such as in [13], blind estimator can be used to recover the carrier-phase offset. In the context of blind phase synchronization, in our previous work in [14], we are particularly devoted to the development of new technique blind carrier phase recovery for SISO systems, particularly for $2\pi/M$ rotationally symmetric constellations. This phase synchronization algorithm provides good performance over competitive estimators. Due its effectiveness and its good performance, we propose in this paper an extension of this phase estimator for STBC coded MIMO systems. In this work, we propose a low-complexity blind carrier phase recovery algorithm suited for multiple antenna schemes based on STBC coding, equipped by two transmit antennas and multiple receive antennas. The phase estimation method is based on a special phase metric that exhibits an absolute minimum at the carrier phase offset. This novel phase synchronizer depends on the rotational invariance of the constellation and the transmit antennas number. Simulation results demonstrate the reliability of the proposed blind phase estimator and its robustness against wide carrier phase offset range.

This paper is organized as follows. In second section, the proposed system is described in the presence of carrier phase offset over fading channels. Section 3 presents the proposed phase synchronizer derived for STBC coded MIMO schemes. The performance analysis and computer simulation results are given in Section 4, and the conclusions are drawn in Section 5.

II. System Model

We consider a MIMO system based on STBC code with two transmit and N_R receive antennas as shown in Fig. 1. We consider here a MIMO channel, H, assumed to be quasi-static fading channel, and known at the receiver side. In this paper, the main focus is on tracking the phase offsets introduced at the receive antennas. Our blind estimation method consists of the extension of our phase offset synchronizer previously proposed for the SISO channels in our work in [14].

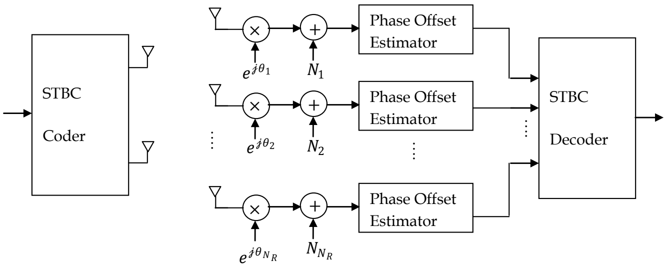

Fig.1. MIMO-STBC System with phase offset

The vector of discrete-time baseband received signal at the receiver side at time t, is given by:

$$Y_t = \Lambda.H.C(S_t) + \eta_t \tag{1}$$

Where

- $\Lambda = [e^{\jmath\theta_1}, e^{\jmath\theta_2}, \dots, e^{\jmath\theta_{N_R}}]$, with $\jmath = \sqrt{-1}$ and θ_k ($k = 1, \dots, N_R$) is random phase offset at the k^{th} receive antenna. It is assumed to be constant over codeword period.
- H is the $N_R \times N_T$ channel matrix, N_T is assumed equal to 2 in this paper.
- η_t denotes the zero-mean complex additive white Gaussian noise at the receive antenna, i.e. $\eta_t \sim \mathcal{CN}(0, \sigma_n^2)$, where σ_n^2 is the noise variance.
- $S_t = (s_{1,t}, s_{2,t})$ is the symbol vector transmitted from the two transmit antennas at time t. Each data symbol belongs to the M-PSK constellation, denoted by A, where $M = 2^b$.
- The STBC coding matrix is given by:

$$C(S_t) = \begin{bmatrix} s_{1,t} & s_{2,t} \\ -s_{2,t}^* & s_{1,t}^* \end{bmatrix} \tag{2}$$

At each receive antenna, a blind phase estimation algorithm is applied to estimate the phase offsets. The phase estimators are followed by the STBC decoder that assumes perfect knowledge of MIMO complex gains. Indeed, we are concerned here only with the phase synchronization. The matrix of the MIMO channel can be estimated by a supervised method.

III. Blind Phase Offset Estimation Algorithm

A. Phase Estimation Metric

For simplicity, we consider, in this section, only one receive antenna. We denote h_1 and h_1 the channel coefficients. $\eta_{1,t}$ and $\eta_{2,t}$ are noise samples at time t. In the presence of phase offset θ_1, the received signals in the first and second instants are given by:

$$\begin{cases} r_{1,t} = (h_1 s_{1,t} + h_2 s_{2,t}) e^{\jmath\theta_1} + \eta_{1,t} \\ r_{2,t} = (-h_1 s_{2,t}^* + h_2 s_{1,t}^*) e^{\jmath\theta_1} + \eta_{2,t} \end{cases} \tag{3}$$

Without loss of generality, the 8-PSK modulation is considered hereafter. Then, the transmitted samples at time t, $\{s_{i,t};\ i = 1,2\}$ belong to the 8-PSK constellation that is π/4-rotationally symmetric. Since the phase error is the same for both $r_{1,t}$ and $r_{2,t}$ signals, it is enough to estimate the phase offset using the set of signals $\{r_{1,t}\}$.

Since our phase synchronization algorithm is based on the principle of phase rotation invariance, it is essential to prove that the signals $X = \{h_1 s_{1,t} + h_2 s_{2,t}\}$ have an angle of phase rotation invariance. Otherwise, it suffices to prove this condition for all $s_x = \{h_1 s_{1,t}\}$ since X is a linear combination of two terms of the same type. Indeed, every element of the set s_x can be written as $s_m = h_1 s_{1,t}$, Where h_1 is a random variable expressed by $h_1 = |h_1| e^{\jmath\varphi}$. Each 8-PSK symbol is denoted by: $s = e^{\jmath 2k\pi/M}$, where $M = 8$ and $k = \{0,1,\dots,7\}$. Then, we obtain:

$$\begin{aligned} arg(s_m) &= arg(h_1 s) \\ &= arg(|h_1| e^{\jmath\varphi} e^{\jmath k\pi/4}) \\ &= \varphi + k\pi/4 \end{aligned} \tag{4}$$

This implies: $k\pi/4 = arg(s_m) - P_H$

Applying now modulo π/4 at the two sides, this implies:

$$(arg(s_m) - \varphi).mod(\pi/4) = 0 \tag{5}$$

Then, we obtain:

$$arg(s_m) = \varphi.mod(\pi/4) + \ell\pi/4 \ ;\ \ell \in \mathbb{Z} \tag{6}$$

Therefore, the set $\{s_m\}$ is π/4-rotationally symmetric. Then, X is also π/4-rotationally invariant. This result is also proved by simulations in Fig. 2 that shows four possible cases of the new constellation with random values of MIMO channel coefficients. Consequently, the random phase offset θ_1 is recovered within a modulo π/4 phase ambiguity. Without loss of generality, we assume that the unknown phase offset θ_1 lies in $[0, \pi/4)$.

In order to estimate the phase offset, we use the phase-metric $M(\theta)$ introduced in [14] for SISO systems:

$$M(\theta) = \sum_{k=1}^{N} min_{a \in C_{ST}} \left\| r_k e^{-\jmath\theta} - a \right\|^2 \tag{7}$$

Where N denotes the number of observed samples {a} runs through the new constellation $X = \{h_1 s_{1,t} + h_2 s_{2,t}\}$ denoted by C_{ST} composed by 64 symbols and θ is an eligible phase within the investigation interval $[0, \pi/4)$.

The same case of SISO system, for each receive antenna, the detector picks the particular angle $\hat{\theta}_1$ within I_1 that minimizes the phase-metric. The set I_1 given by (8) is composed by $(n-1)$ discrete phases uniformly distributed in $[0, \pi/4)$. N should be suitably chosen so that the observed sample set involves all channel signals with equal probability.

$$I_1 = \left\{\theta_p = p\frac{\pi}{4n}\,; 1 \leq p \leq (n-1)\right\} \qquad (8)$$

In order to measure the performance of the phase-metric (3), we consider a finite set of n discrete phases uniformly distributed in the interval I_1. As shown in Fig. 3, the phase metric $M(\theta)$ defined in (7) has a unique minimum for the new constellation where the phase error is chosen equal to $\theta_1 = 15°$ and the SNR is 26 dB. The number of observation samples, N, is 500. In addition, the number of discrete phases n is chosen equal to 50. These results confirm that the minimum one is obtained near to θ_1. Therefore, the proposed phase estimator suitable for MIMO systems is unbiased.

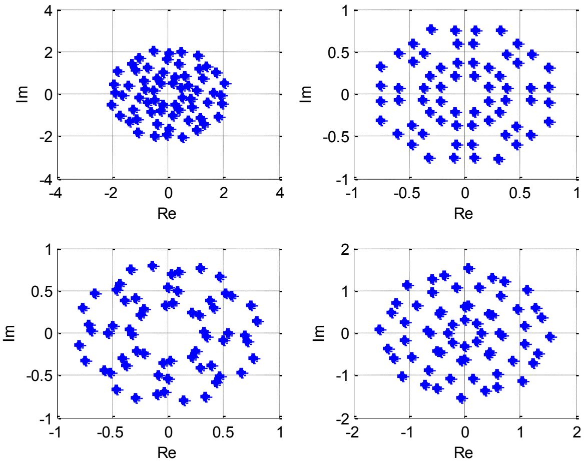

Fig.2. Examples of the novel consellation X

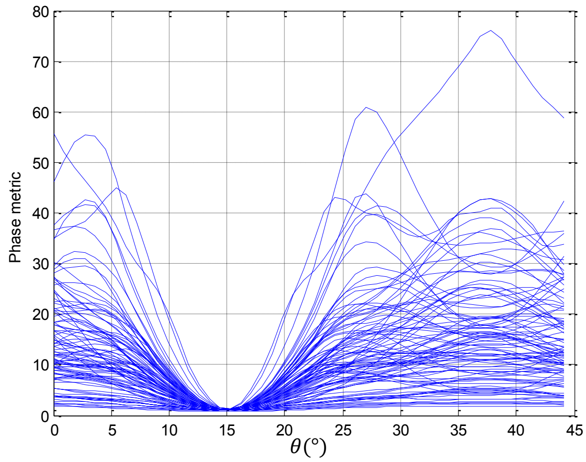

Fig.3. Phase Metric, $\theta_1 = 15°; SNR = 26\ dB;\ N_T = 2;\ N_R = 1$

B. Phase estimator and its standard deviation

Assuming one receive antenna, our blind phase estimator stars by picking up the particular angle $\theta_{\tilde{p}}$ $(1 \leq \tilde{p} \leq (n-1))$ within I_1 that minimizes the phase-metric according to the following equation:

$$\theta_{\tilde{p}} = \text{argmin}_{\theta_p \in I_1}\left(M(\theta_p)\right) \qquad (9)$$

After the first stage, better estimation precision of the phase offset is achieved at the second stage by limiting the search to the subinterval $[(\tilde{p}-1)\pi/4, (\tilde{p}+1)\pi/4)$ only. Thus, the new set of discrete phases is uniformly distributed in the subinterval given by:

$$I_2 = \left\{\theta_q = (\tilde{p}-1)\frac{\pi}{4n} + q\frac{\pi}{2n^2}; 0 \leq q \leq n\right\} \qquad (10)$$

Note that in the second stage, the same phase-metric is also used but in the subinterval I_2. Therefore, the phase offset is estimated according to the following equation:

$$\hat{\theta}_1 = \text{argmin}_{\theta_q \in I_2}\left(M(\theta_q)\right) \qquad (11)$$

The performance of our phase estimator based on two stage is studied here by considering the new constellation, $X = \{h_1 s_{1,t} + h_2 s_{2,t}\}$, having an angle of invariance phase rotation $\pi/4$. Simulation results in Fig. 4 show the standard deviation of our phase estimator adapted to the MIMO channels for quasi-static Rayleigh. The considered STBC coded MIMO system is equipped by two transmit antennas and one receive antenna. The phase offset is randomly chosen in the range $[0, \pi/4)$. The number of samples N is selected equal to 160. We note that if the number of discrete phases n increases, the performance of the phase estimation method become best at a price of increased computational complexity.

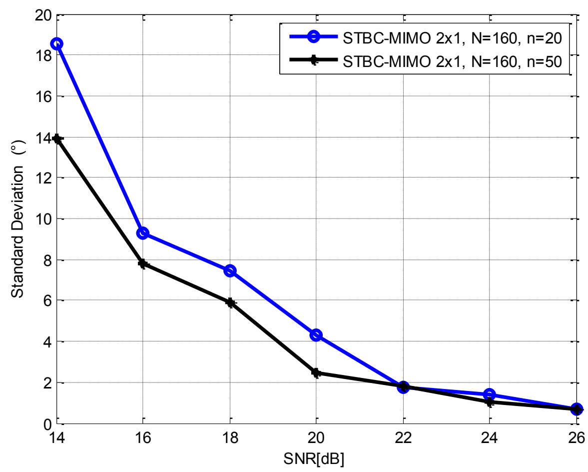

Fig.4. Standard Deviation of the novel phase synchronizer, N=160.

C. Phase estimation algorithm applied to STBC coded MIMO

In this subsection, our blind phase estimation algorithm proposed for MIMO systems based on Alamouti STBC code is studied assuming a single receiver antenna. For MIMO systems equipped by N_R receive antennas, the last phase estimation technique is repeated N_R times. Alternatively, in multi-antenna systems, N_R phase estimators are used to compensate for N_R

phase offsets. At each receiving antenna, the proposed synchronization algorithm is the blind phase estimator, inspired from the phase synchronizer designed for SISO systems. Notice that the novel algorithm is followed by a modified phase metric update unit.

The proposed algorithm is the two-stage estimator defined in subsection B followed by phase metric updating unit. In the output of the second stage, the estimator does not record the discrete phase $\theta_q \in I_2$ that minimizes the phase metric given by (8), but records only the minimal metric value, denoted by ζ:

$$\zeta = min_{\theta_q \in I_2}\{M_{t=NT}(\theta_q)\} \quad (12)$$

Where T is the modulation interval that is considered as perfectly known at the receiver side. This phase metric is updated continuously. Therefore, the computation of successive phase metrics $\{\Omega(\theta_q)\}$ for each discrete phase θ_q in I_2 starts at time $t = (N+1)T$. The phase metric is recursively updated in the next time steps until $t = (N+B)T$ corresponding to B received samples that follow the received symbols used in the two stage. For $(N+1) \le i \le (N+B)$, the phase metric can be expressed as follows:

$$\Omega_{t=iT}(\theta_q) = \zeta + \sum_{w=(N+1)}^{k} \beta_{t=wT}(\theta_q) \quad (13)$$

Where $\beta_{t=wT}(\theta_q) = min_{a \in C_{ST}} \left\| r_w e^{-j\theta_q} - a \right\|^2$.

At each step $t = iT$, $(N+1) \le i \le (N+B)$, we note the carrier phase by:

$$\hat{\theta}_t = argmin_{\theta_q \in I_2}\{\Omega_t(\theta_q)\} \quad (14)$$

Thus, the set of estimated phases for $(N+B)$ 8-PSK received samples is given by:

$$\Psi = \{\hat{\theta}_{(N+l)T_s} ; 1 \le l \le B\} \quad (15)$$

The detector records the number of occurrence of each discrete phase $\hat{\theta}_{(N+l)T_s}$ that minimizes the phase metric during the interval $[(N+1)T, (N+B)T]$. The particular phase with the highest probability in the set Ψ is the optimal estimate of the phase.

After the step of estimating the phase offset θ_1, the received signals $\{r_{1,t}\}$ and $\{r_{2,t}\}$ are multiplied by $e^{-j\theta_1}$. Finally, the STBC decoder is applied with a perfect knowledge of the MIMO channel coefficients. This phase estimation algorithm remains valid for multi-antenna systems based on orthogonal STBC coding and also for other types of constellations, but with a modification in the metric phase $M(\theta)$. Also the complexity of this method of synchronization slightly increases with the number of transmit antennas, N_T.

IV. RESULTS

In this section, we present the proposed coherent system performance in terms of FER (Frame Error Rate). In all simulations, only the 8-PSK modulation is considered. Two cases of Alamouti STBC coding are considered: one and two receive antennas. The Rayleigh flat fading MIMO channel is assumed to be constant for each size of data frame 130 symbols and varies from one frame to another. At each receive antenna, the received signals associated with the first period of STBC code word are used to blind estimation of the phase error is assumed to be constant on the data frame. Thus, the blind estimator described in section 3 is applied using the phase metric given by (7). Finally, the STBC decoder is applied to the received signals and compensated for phase offsets with a perfect knowledge of MIMO channel coefficients.

To evaluate the performance of our phase synchronization algorithm on MIMO systems, we proceed by comparing the performance in terms of FER our system with that of the ideal case. In Fig. 5, we present the FER as a function of signal-to-noise ratio (SNR), of the new proposed MIMO systems.

These curves show that the performance of the proposed coherent schemes is nearly to 0.5 dB loss compared to ideal systems.

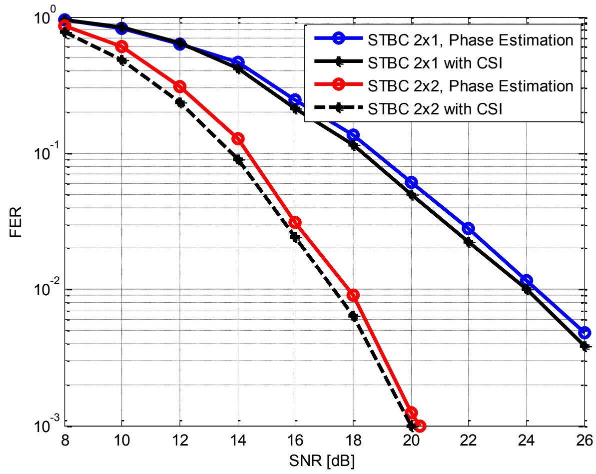

Fig.5. FER performance of STBC coded MIMO with phase estimation

V. CONCLUSION

In this contribution, we have studied the effect of carrier phase offsets on the performance of STBC coded MIMO systems equipped by two transmit antennas and N_R receive antennas. To overcome this drawback, we investigate a blind carrier phase estimation algorithm based on a special phase metric. By comparison to the perfectly synchronized schemes, the proposed coherent STBC coded MIMO systems introduce negligible performance loss. Furthermore, the proposed blind estimation method stands applicable for massive MIMO systems.

REFERENCES

[1] S. M. Alamouti, "A Simple transmit diversity technique for wireless communications," IEEE Journal on Selected Areas in Communications, vol. 16, pp.1451-1458, Oct. 1998.

[2] Petre Stoica and Girish Ganesan, "Trained Space-Time Block Decoding for Flat Fading Channels with Frequency Offsets," Wireless Personal Communications, vol. 27,pp. 235–245, 2003.

[3] Shahram Shahbazpanahi, Alex B. Gershman and Georgios B. Giannakis, "Blind and Semiblind Channel and Carrier Frequency-Offset Estimation

in Orthogonally Space-Time Block Coded MIMO Systems," IEEE Transactions on Signal Processing, vol.56, no.2, pp.702-711, February 2008.

[4] Z. Liu, G. B. Giannakis, and B. L. Hughes, "Double differential space-time block coding for time-selective fading channels," IEEE Transactions on Communications, vol. 49, no. 9, pp. 1529-1539, Sep. 2001.

[5] Emna Ben Slimane, Slaheddine Jarboui and Ammar Bouallègue, "An Improved Differential Space-Time Block Coding Scheme Based on Viterbi Algorithm," IEEE Communications Letters, vol. 17, no. 9, pp. 1707–1709, September 2013.

[6] Emna Ben Slimane, Slaheddine Jarboui and Ammar Bouallègue, "Compensation of Phase Offsets in MIMO Systems Using an Efficient Differential STBC," The 11th IEEE International Wireless Communications & Mobile Computing Conference (IWCMC), Croatia, August 2015.

[7] Yan Wang, Erchin Serpedin and Philippe Ciblat, "Optimal Blind Carrier Recovery for MPSK Burst Transmissions," IEEE Transactions on Communications, vol. 51, No. 9, September 2003.

[8] Giuseppe Durisi, Alberto Tarable, Christian Camarda, Rahul Devassy and Guido Montorsi, "Capacity bounds for MIMO microwave backhaul links affected by phase noise," IEEE Transations on Communications, vol.62, no.3, pp.902-929, February 2014.

[9] Hani Mehrpouyan, Ali A. Nasir, Steven D. Blostein, Thomas Eriksson, George K. Karagiannidis, and Tommy Svensson, "Joint Estimation of Channel and Oscillator Phase Noise in MIMO Systems," IEEE Transactions on Signal Processing, vol. 60, no. 9, September 2012.

[10] A. Tarable, G. Montorsi, S. Benedetto and S. Chinnici, "An EM-based phase-noise estimator for MIMO systems," The IEEE International Conference on Communications. (ICC), pp. 3215 – 3219, June 2013, Budapest, USA.

[11] N. Hadaschik, M. Dorpinghaus, A. Senst, O. Harmjanz, and U. Kaufer, "Improving MIMO phase noise estimation by exploiting spatial correlations," in Proc. IEEE Acoust., Speech, Signal Process. (ICASSP), Philadelphia, PA, Mar. 2005, vol. 3.

[12] Tim Zhong Mingqian, A. B. Premkumar, A. S. Madhukumar, "Performance investigation of STBC-OFDM systems with frequency offset and a semi-blind approach for the correction," The 59th IEEE Vehicular Technology Conference (VTC-Spring), Milan, May. 2004, pp. 1836 - 1839.

[13] A. M. Rabiei and N. C. Beaulieu, "Frequency Offset Invariant Multiple Symbol Differential Detection of MPSK," IEEE Transactions Communications vol. 59, no. 3, pp. 652-657, March 2011.

[14] Emna Ben Slimane, Slaheddine Jarboui and Ammar Bouallègue, "Blind carrier phase recovery for general 2π/M-rotationally symmetric constellations," International Journal of Wireless & Mobile Networks (IJWMN) Vol. 4, No. 1, February 2012.