Non-Reference Metrics and Its Application for Distortion Compensation

Andrey Kiselnikov, Mikhail Dubov, Andrey Priorov
P.G. Demidov Yaroslavl State University
Yaroslavl, Russia
{a.kiselnikov, m.dubov}@uniyar.ac.ru, andcat@yandex.ru

Abstract–**This article summarizes the SNR estimation methods and suggests a relatively simple SNR method for estimating blind signals for QAM and PSK modulation signals. The proposed modification of this method allowed to accurately estimate the BER or SER with a transaction of a relatively small number of symbols and a minimal error without any reference sequences. A practical application of this method is also provided - compensation of the BPSK signal offset using AWGN in the channel.**

I. Introduction

The most of the modern communication systems use spectral efficient modulations like a QAM or M-PSK. By the way increasing the number of channel symbols requires better communication channel [1-5]. So the most of the up to date communication systems like WCDMA or LTE are adaptive and uses different modulation dependent to the channel quality. The chosen modulation method is the result of the compromise between channel quality and required speed. Also all digital communication systems have a threshold effect when the system works near the limit of channel codec and any minimal deterioration of channel quality can drop the communication.

In most cases, the resulting criterion of communication system reliability is bit error ratio (BER) or symbol error ratio (SER). Measurement of these criterions performed by the transaction of etalon sequences or based on channel decoder messages [6]. This approach requires existing of the reference sequences and a huge number of transacted symbols for decreasing resulting error. Moreover, there is valuable time and measurement error dependence from a number of transacted symbols. For example, you should transact 10^{-6} symbols to achieve an applicable accuracy 10^{-5}. Also, there are some measurement systems that gives the result only after they had fixed 100 errors.

In practical case will be useful to have an approach for marking the probability of bit error based on the received signal without any etalon sequences. There are no ways for evaluation of BER without knowledge about the transacted message. However, for each modulation type, there is functional dependence between BER and a signal to noise ratio. So if there is a method of measurement SNR in channel BER can be calculated with using dependence described above. The valuable disadvantage of this approach is that it is applicable only with additional white Gauss noise distortion any other distortions like frequency selective fading can't be considered to this approach.

There are too many sources devoted to the theory of the statistical radio systems in that exactly described method of the evaluating different parameters of the received signal, by the way evaluating dispersion of the received signal is the complicated and sparingly described task. In cases when the dispersion of channel noise is unknown value adaptive methods are more applicable, but they don't solve dispersion evaluation task. Theory of adaptive method synthesis as well as optimal methods described in [7]. Also up to date number of the patents devoted to this method still increasing.

The scope of this work is proposing simple SNR estimation method for QAM and PSK modulations and a distortion identification algorithm on the example of BPSK signal constellation.

II. Signal distortion evaluation metrics

For the generality of reasoning, we should make some overview of classic distortion evaluation metrics: signal to noise ratio (SNR), carrier to noise ratio (CNR), bit energy to noise spectral density ratio. SNR metric is the ratio between average signal power and average noise power in the signal band. Under the signal, we understand baseband signal based on low frequency before modulator in the transmitter or after demodulator in the receiver. CNR metric is the ratio between average carrier power and noise power in the noise band that defines transmitter radio circuits after modulator or receiver radio circuits before demodulator. So the main disadvantage of these methods is the fact that they do not consider the inner band distortions and there are cases when SNR or CNR metric shows high value but the signal is strongly distorted. These metrics more applicable for analogue modulation technics.

The energy of bit or symbol to the average noise spectral density E_b/N_o or E_s/N_o is appropriate quality measurement metrics for the digital signals. However, these metrics don't characterize some types of digital modulation like quadrature modulation methods. By the way, this metrics are applicable for evaluating the quality of the quadrature signals and applied in practical cases.

The appropriate metric for the quadrature signals is the evaluating of the deviation value between real symbol vectors in the quadrature coordinate system and their reference points [8-9]. Description of three most spreader metrics will be listed below.

Modulation Error Ratio (MER) is the ratio between average symbol power and average error power that represented in decibels. In this definition, it is easy to mix MER and SNR but the last defined for baseband signals and MER exactly for quadrature signals. So we can say that MER is a digital variation of the SNR for quadrature signals:

$$MER = 10\lg\frac{P_a}{P_{er}}, \tag{1}$$

where P_a is average power of the signal constellation and P_{er} is average power of error.

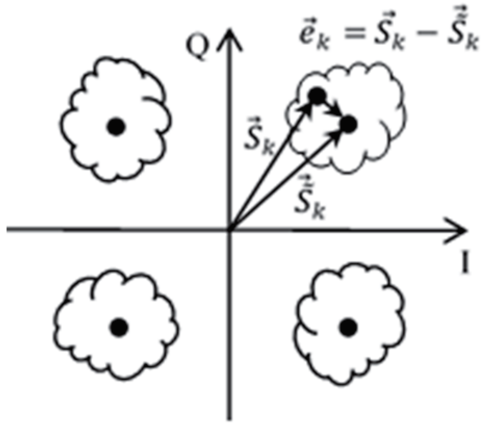

Fig. 1. Error vector concept

In the definition of error power used vector concept the difference between transmitted S_k and received $\tilde{S}_k$ symbols (Fig. 1). Using the vector concept we can perform MER definition for the frame that contains the N symbols:

$$MER = 10\lg\frac{\sum_{k=1}^{N}\left(I_k^2 + Q_k^2\right)}{\sum_{k=1}^{N} e_k^2}, \tag{2}$$

where I_k and Q_k are in-phase and quadrature coordinates of the received symbol and the error vector magnitude define by nest equation:

$$e_k^2 = \left(I_k - \tilde{I}_k\right)^2 + \left(Q_k - \tilde{Q}_k\right)^2. \tag{3}$$

So MER is the direct and appropriate metric for the distortion evaluation of the quadrature signals. By the way, this metric can be related to reference metrics type because for it calculation should be known both received and transmitted signals.

In other case, instead of originally transmitted coordinates may be used coordinates that were recovered by the demodulator in the receiver. This variation of MER metric can be related to the non-reference metrics type. This type of metrics is applicable only to the modulation types with limited channel symbols number, digital signals exactly correspond to this criterion. We will add the "R" letter to the definition of this metrics. This letter means "receive" [10]. So the non-reference variation of the MER will be called RMER.

In the few sources there is the definition of the MER separately to each symbol of the signal constellation inside k-frame:

$$MER_k = 10\lg\frac{\frac{1}{N}\sum_{k=1}^{N}\left(I_k^2 + Q_k^2\right)}{e_k^2}. \tag{4}$$

Also, should be noted that in the case when signal distorted only with AWGN and channel band equals to symbol speed according to Nyquist criterion reference MER will be equals to SNR:

$$SNR = E_s / N_0 = MER. \tag{5}$$

Error Vector Magnitude is the ratio between the average square deviation of the received symbols relative to their reference points and the average magnitude of the received constellation. This metric can be represented in percent's:

$$EVM = \sqrt{\frac{\sum_{k=1}^{N} e_k^2}{\sum_{k=1}^{N}\left(I_k^2 + Q_k^2\right)}} \cdot 100\% = \sqrt{\frac{P_{er}}{P_a}} \cdot 100\%. \tag{6}$$

This metric is reverse proportional to MER. Also, EVM can be defined for each symbol in a frame like MER:

$$EVM_k = \sqrt{\frac{e_k^2}{\frac{1}{N}\sum_{k=1}^{N}\left(I_k^2 + Q_k^2\right)}} = \frac{|e_k|}{\sqrt{P_a}}. \tag{7}$$

Listed above metrics are invariant linked between each other. So each of them can be represented by another:

$$MER[dB] = 10\lg\frac{1}{EVM^2} = -20\lg EVM. \tag{8}$$

The main problem in using non-reference metrics is that in error case EVM will be smaller or higher than it is because detector with a hard decision will attract it to the nearest constellation point (Fig. 2). For example, RMER will be higher than MER. In the telecommunication guides, this moment is noted but no solution was not represented. Assumed that MER is incorrect when symbol error is higher than 10^{-2}.

So the measurement equipment limited by the RMER value related to BER like 10^{-2} – 10^{-3}. It is called a failure threshold. Of course, this threshold has dependence from modulation type and listed in Table I.

TABLE I. PRACTICAL RMER MEASUREMENT THRESHOLD

Modulation type	Measurement threshold, dB
BPSK, QPSK	7-10
QAM-16	15-18
QAM-64	22-24
QAM-256	28-30

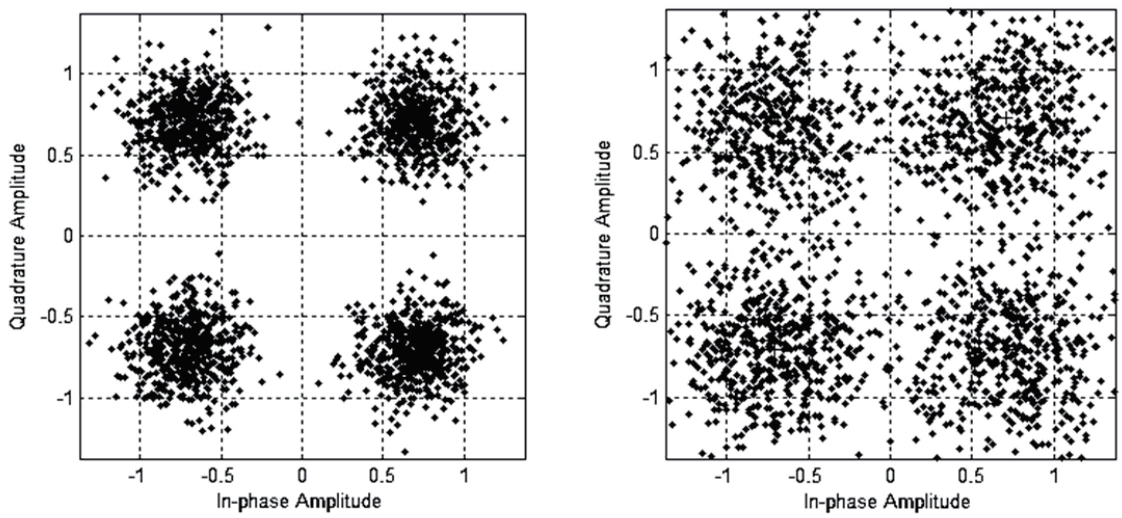

Fig. 2. Signal constellation with low and high noise

The upper threshold of the most measurement equipment is limited by value about 40-45 dB anyway for the ideal signal without noise. The reason is inner equipment noise. In addition should be noted the fact that modern equipment measures BER and SER that allow making a decision about reliability RMER, and typical measurement error defined RMER ± 2dB [11].

For the analysis of the non-reference metrics behavior in the case when SNR ratio is bellow then measurement threshold, was performed model research of communication system in Matlab software package [12]. On the Fig. 3 represented block-scheme of the experimental model with MER and RMER calculation. During all experiment average power of the signal constellation maintained at the constant level.

On the Fig. 4 represented experimental dependences of averaged on K =100 frames (any of each frame consist of 1000 symbols) MER values, calculated in reference to original and recovered constellation for different QAM orders. So referred to the graphics we can make a conclusion that under the defined value of the E_b/N_o all non-reference results are worst in comparison with reference metrics, exactly RMER has method error 2–9 dB. This method error becomes exactly thresholds represented above (Table 1). The one valuable fact should be noted – there are no the same RMER values for different E_b/N_o ratios. RMER function monotone increase according to SNR increasing. This fact allows using RMER for invariant recovering the true SNR ratio and increasing the measurement equipment abilities. Now make a comparison between reference and non-reference EVM calculation. The scheme of the experiment is the same with represented on the Fig. 3, of course excluding measures. The results of these experiments are represented in the Fig. 5.

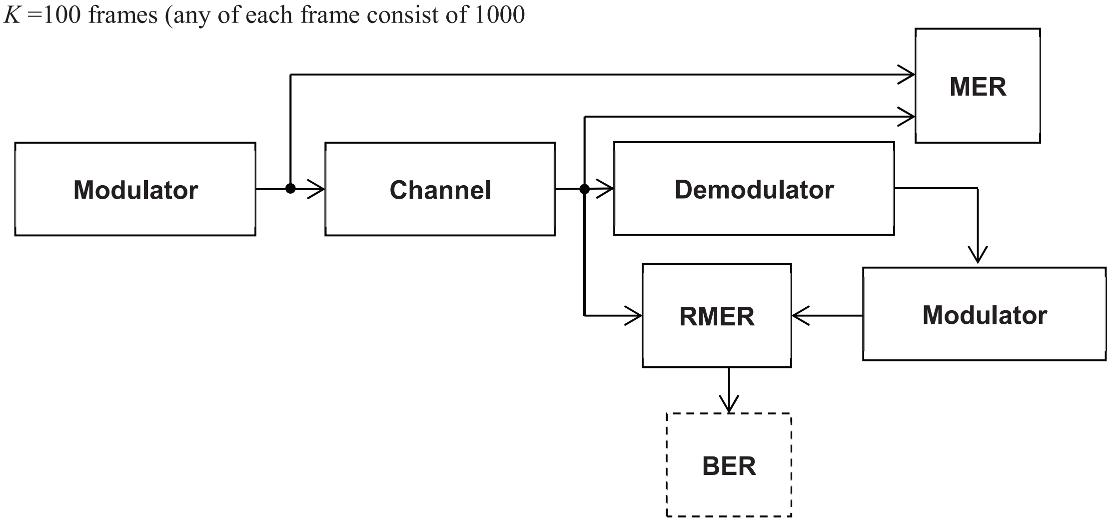

Fig. 3. Experimental model for MER and RMER calculation

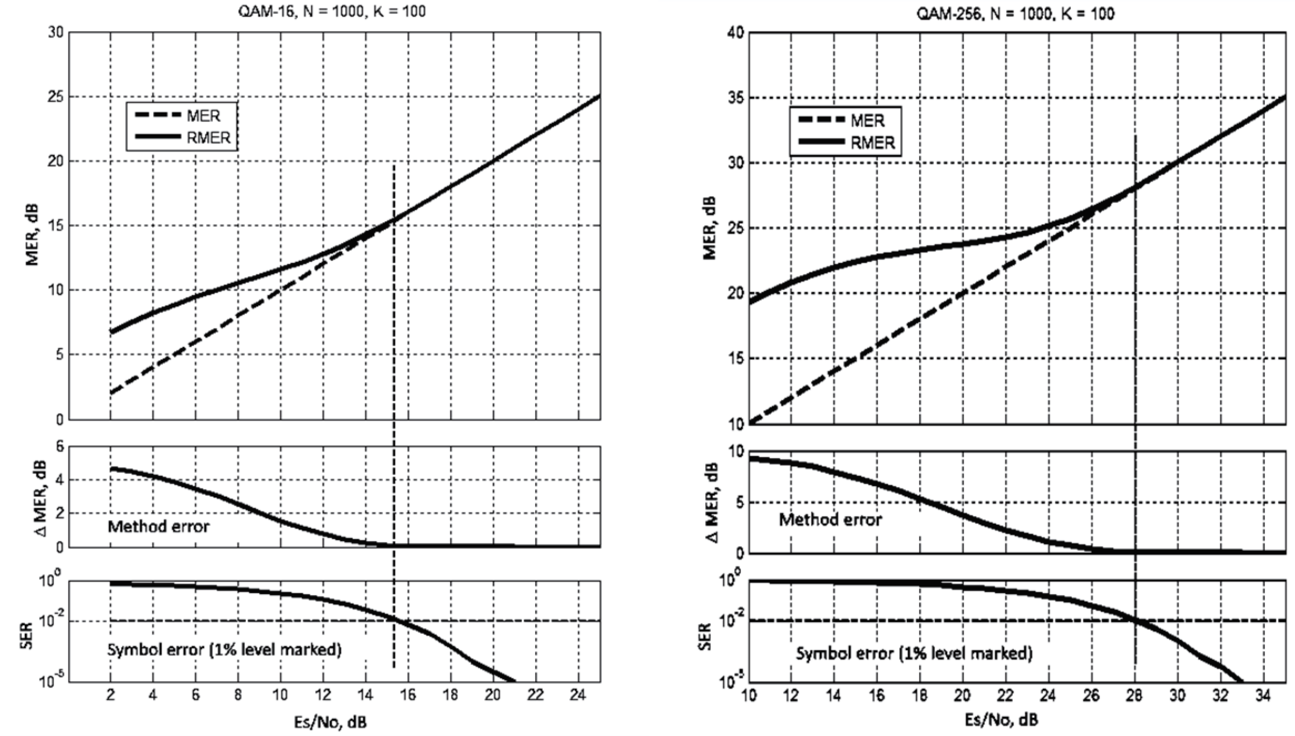

Fig. 4. MER and RMER measurements

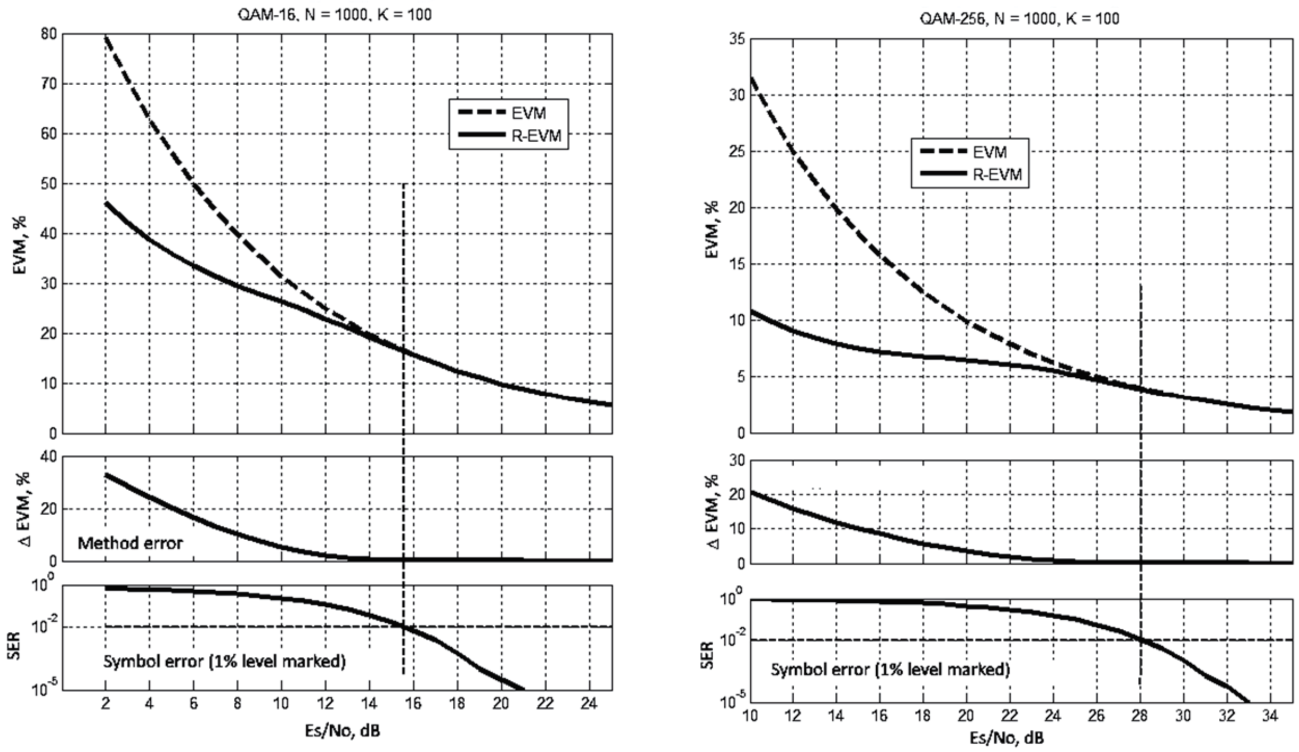

Fig. 5. EVM and R-EVM measurements

The non-reference metric shows unreliable results when SNR ratio is low. MER can be used anyway because there is an invariant dependence between EVM, MER and SNR and MER is more applicable in practice case then other metrics.

III. Signal to noise evaluation approach

There is a known modulation type (BPSK, 4QAM/QPSK, 16QAM, 64QAM, 256 QAM) with only AWGN distortion factor. Quantizer noise does not matter. Also, there are no any reference sequences. The task is to evaluate SNR ratio in the receiver with hard decision detector. For this evaluation will be using a non-reference metric RMER. These metric giver reliable results without offset when SNR is better than $SER < 10^{-2}$. That is equal to the difference for each modulation type threshold of the SNR. In the case when SNR is below threshold there is systematic error that depends on the real ratio between signal and noise in the channel. So the RMER value should be corrected.

There are two error correction approaches, which can be applied in dependence on hardware realization of the receiver.

The first way represents as calibration table with the defined step that defines approach resolution. It will take a lot of memory and requires a small number of calculation. The second way represents as the polynomial approximation of the resulting line bellow reliable threshold, it will be chosen.

Polynomial coefficients can be found with using least squares method:

$$\frac{E_s}{N_0} = a_0 + a_1\left(RMER\right) + a_2\left(RMER\right)^2 + \ldots \tag{9}$$

The result of coefficients calculation represented in Table 2.

Should be noted that line on fig. 5 related to the non-reference metric is the result of the analysis of the huge number of symbols. The real practical results will be dissipated near it with the defined error that is a future of any probability method.

IV. Bit error ratio evaluation approach

The metric listed above can be applied for evaluation of the bit or symbol error ratio as well as evaluation of the SNR. In the case when there is QAM modulated signal that distorted only by AWGN noise and quantizing effects does not matter there are three steps of the BER or SER evaluation approach [13].

The first is RMER measurement by recovered with using optimal detector constellation. The second is correcting results in the case when *Es/No* bellow threshold for chosen modulation.

The last step is the calculation of BER using the next modified equation:

$$BER \approx \frac{4}{k}\left(1 - \frac{1}{\sqrt{M}}\right)Q\left\{\sqrt{\left(\frac{3}{M-1}\right)RMER}\right\}, \tag{10}$$

where k is the number of bits or symbols, M is modulation order, $Q(x)$ is the error function defined in [7]. The proposed methodic represents the principal different approach for evaluation of BER in relation to a classic metrics (Fig. 6).

V. The effect of constellation distortion

So all described above metrics use as a basis assumption that there is only AWGN and there are no linear or nonlinear distortions of the signal constellation. When any other distortion adds to the AWGN influence BER can’t be calculated by using modified RMER method. By the way, methodic for separation of AWGN and offset influence can be proposed. In the next part of this article, one of each will be discussed on the simplest case – BPSK modulation, anyway it can be extrapolated for all MPSK modulations.

In BPSK demodulation process the most difficult to elimination distortion is turn of the signal constellation, because signal to noise ratio in receive band still high but the reliability of communication system valuable decrease. This distortion can arise when signal is passing through city building as well as it can be caused by incorrect functionality of receiver radio tract.

Let’s consider the second case closer. Block diagram of typical low-cost quadrature receiver represented at the Fig. 7 from left to right: antenna and low noise amplifier, band filter, quadrature demodulator, lowpass filters for each quadrature signal, ADC and any digital device like a MCU. In this case of hardware realization, there is analogue lowpass filter in each quadrature signal. To achieve high characteristics the next features should be required from quadrature filters: high level of suppression in stopband, minimal distortions in the passband and minimal width of the transition band. These features are appropriate for analogue filters with high orders [14], one of the examples represented on the Fig. 8.

TABLE II. Polynomic coefficients

Modulation	a_0	a_1	a_2	a_3	a_4	a_5	σ, dB	*D*, dB
4-QAM	-2,672	1,518	-0,023	-	-	-	0,02	0..7
16-QAM	5,559	-2,959	0,455	-0,014	-	-	0,1	0..15
64-QAM	-62,35	19,845	-2,300	0,1181	0,0021	-	0,25	0..22
256-QAM	169,43	-59,35	7,898	0,498	0,0151	-0,0002	0,5	0..28

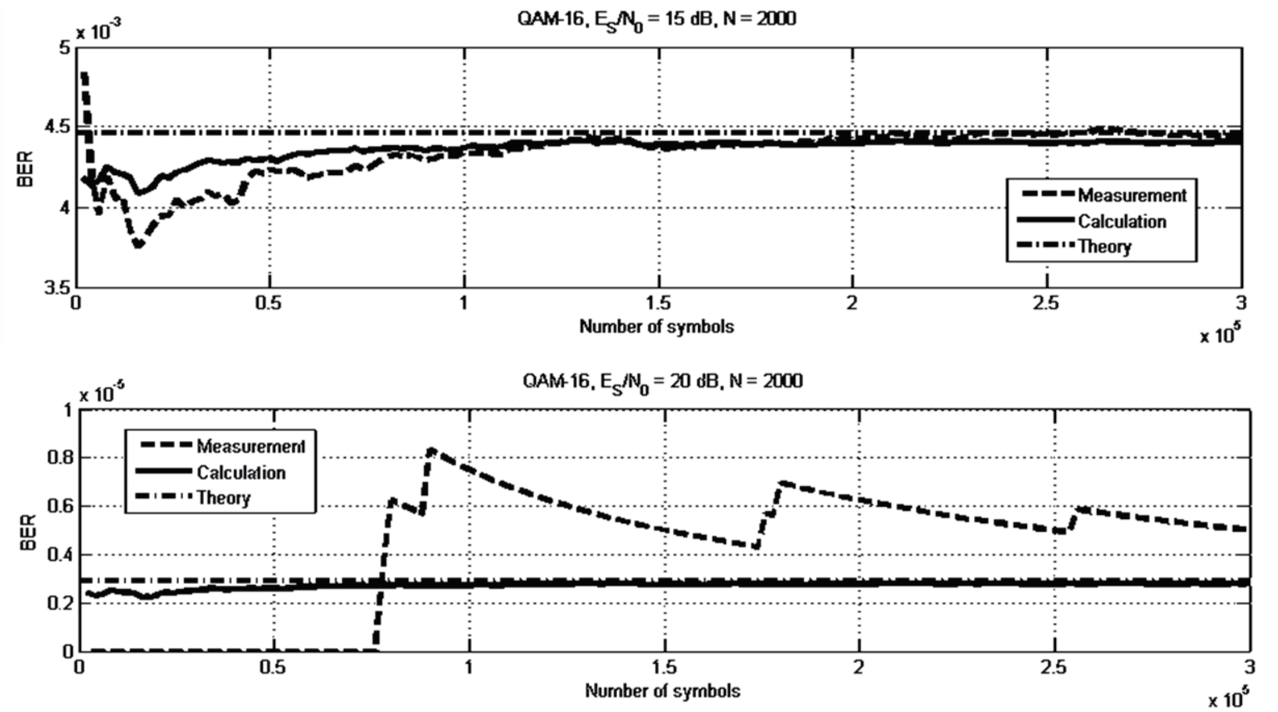

Fig. 6. BER measurements for proposed and classical methodic

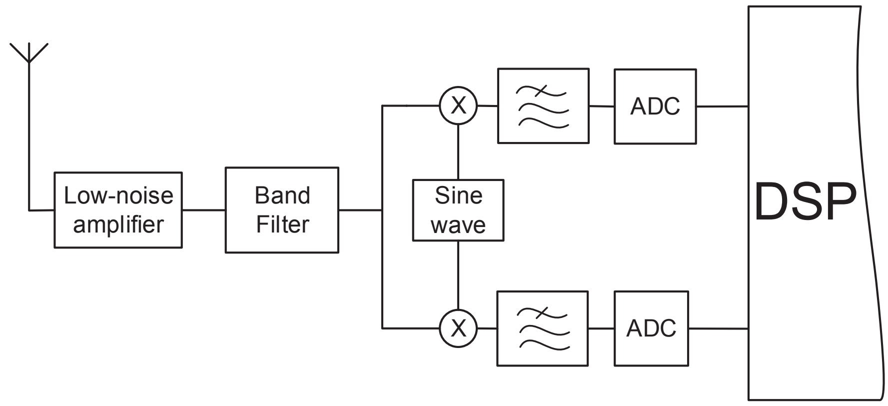

Fig. 7. Quadrature receiver scheme

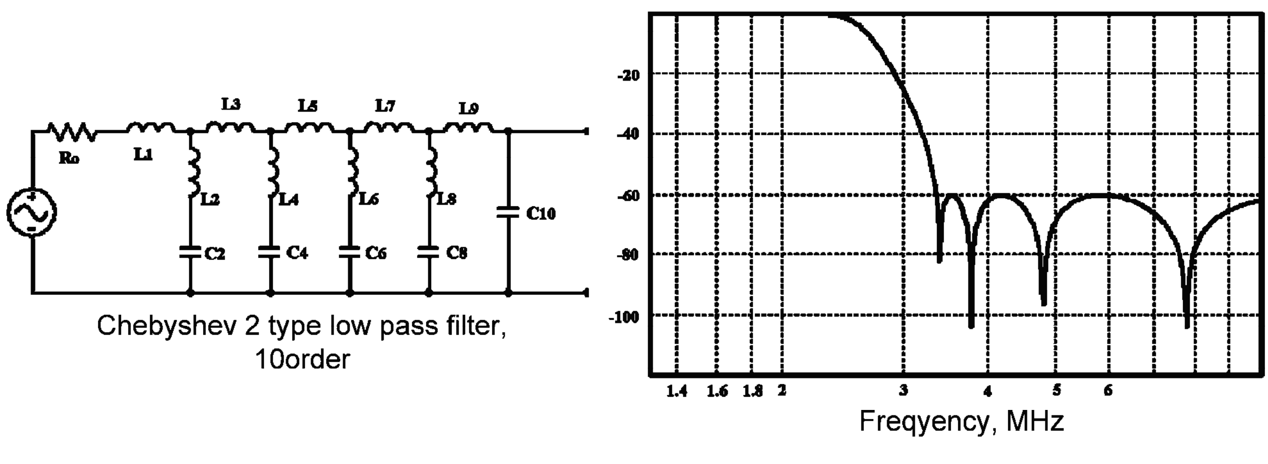

Fig. 8. Principal scheme and magnitude response of low pass filter for quadrature receiver

High order of the analogue filter requires a using a large number of electronics components, if these components are cheap the magnitude and phase response of each quadrature filter can have valuable differences. In some cases, the characteristics of the electronic components can change their values with time or under influence of aggressive factors like a high temperature or vibration. So it can cause quadrature imbalance and turn the signal constellation. An algorithm for the received BPSK signal quality assessing is developed. It allows distinguishing the signal constellation distortion effects and AWGN acting on the signal. The main feature of the algorithm is the use of a received signal quality mixed metric, which includes the elements of the standard metrics (BER) and the non-reference metrics REVM.

V. Communication system with BPSK reliability analysis when signal constellation is distorted

In the first case will be considered the reliability of BPSK signal distorted only by AWGN and E_b/N_o ratio is defined value.

In coherent receive case, BPSK signal constellation represented in quadrature coordinates by two vectors with magnitude $\sqrt{E_S}$ and the quadrature component equalize to zero. So, in this case, BER can be defined by next equation [15-17]:

$$BER = \frac{1}{2}[1 - erf\left(\sqrt{\frac{E_b}{N_0}}\right)], \tag{11}$$

where *erf*() is Laplace function. At the Fig. 9 represented two cases of BPSK signal receive, *S* is a received symbol and μ and σ are central and initial moments of the AWGN. In the distorted case, modified equation for BER calculation can be applied:

$$BER_{dist} = \frac{1}{2}[1 - erf\left(\cos(\varphi)\sqrt{\frac{E_b}{N_0}}\right)]. \tag{12}$$

VI. Offset identification and compensation algorithm

First of all, we should analyze current BER using any way like a decoder message or any pilot signal. If BER meets requires there are no reasons to switch on algorithm to reducing battery consumption. In other case, REVM should be analyzed. If there is no distortion factors the feedback power control system can be activated of course if this future exists. If distortion factor eliminated the compensation parameters should be calculated and applied to the receiver. Than algorithm returns to the beginning.

After review, we should describe each step of the algorithm properly (Fig. 10). After receiving the channel symbol and soft decoding there are there are *I* and *Q* values that defines symbol $\hat{S}$ in IQ coordinates. When one frame was received those values stored as coordinates array:

$$\hat{S}_i = \{I_i; Q_i\}. \tag{13}$$

Also, this values can be accumulated from one frame as well as aggregated from different frames. So when accumulation is finished we should to normalize error vector according to average signal power and then we can evaluate average error vector. The next equation represents normalization coefficient[18,19,20]:

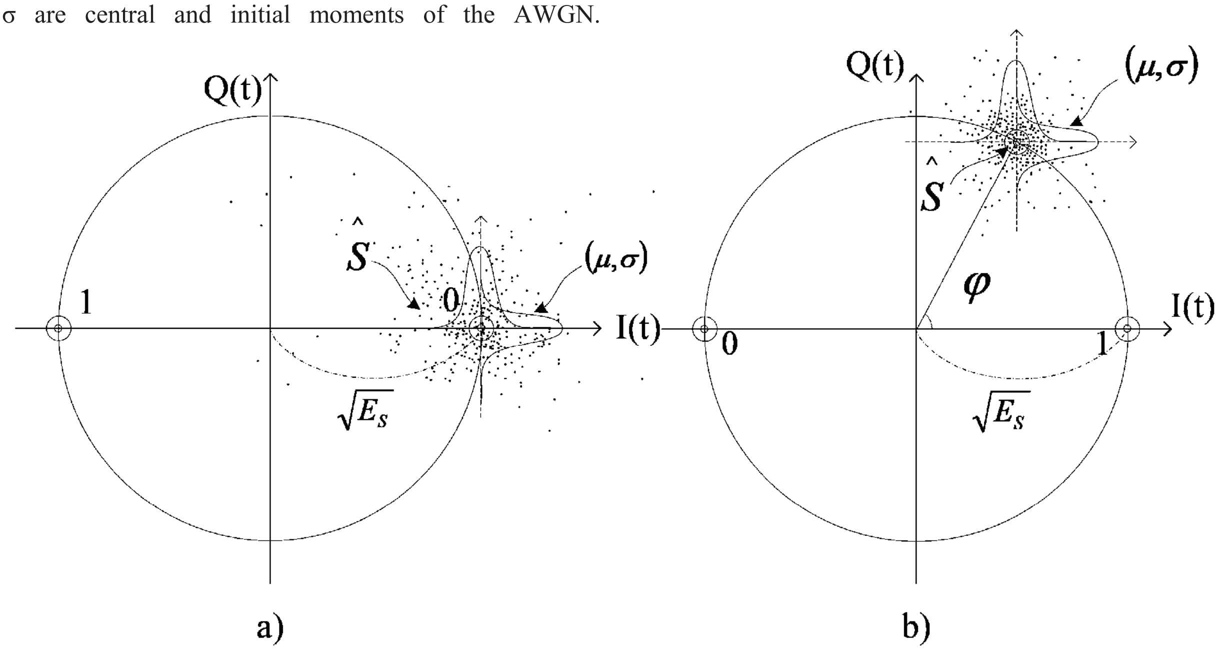

Fig. 9. Distortion influence on BPSK signal: a) AWGN only, b) AWGN and constellation offset

$$A = \sqrt{\left(\sum_{i=0}^{k} \frac{P(\hat{S}_i)}{M}\right)^{-1}}\,, \tag{14}$$

where M is modulation order, $P(\hat{S}_i)$ is symbol energy and k is the number of totally received symbols or frame size. As known all symbols of the PSK modulations have the same energy we can easily compensate constellation distortion because there is only one case when it shifted on the same corner. This corner can be calculated by this equation:

$$\bar{\varphi}(k) = \arccos\left(\frac{1}{2} A\, \overline{EVM}(k) - \sqrt{\bar{E}_s}\,\right), \tag{15}$$

where k is a frame size, E_s – average symbol energy and EVM is error vector calculated by non-reference approach. Additionally, this equation illustrated in Fig. 11.

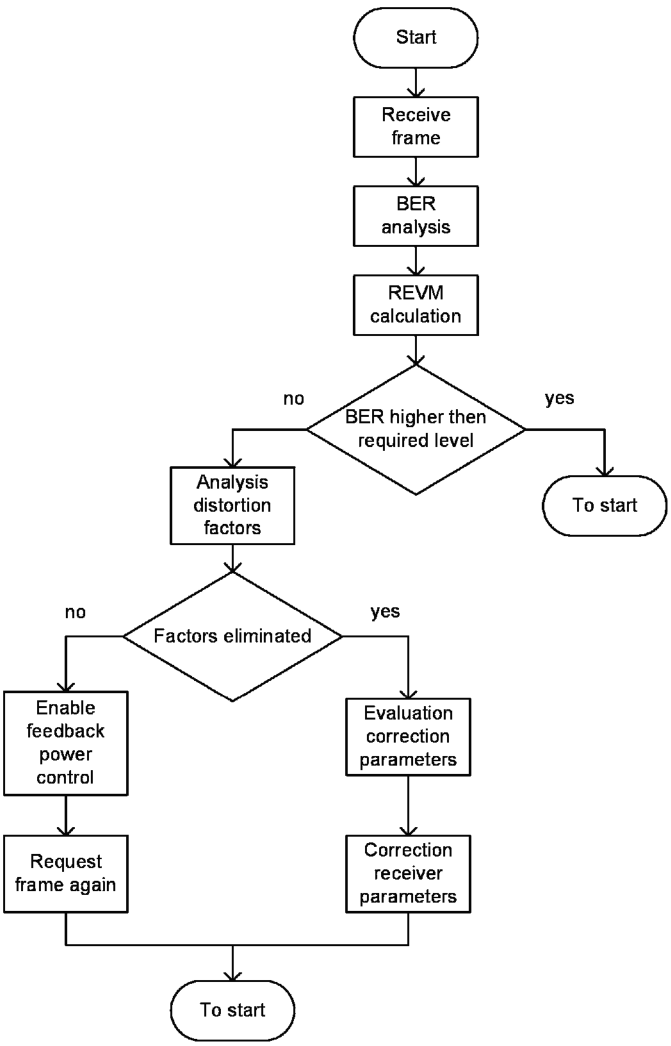

Fig. 10. Offset identification algorithm

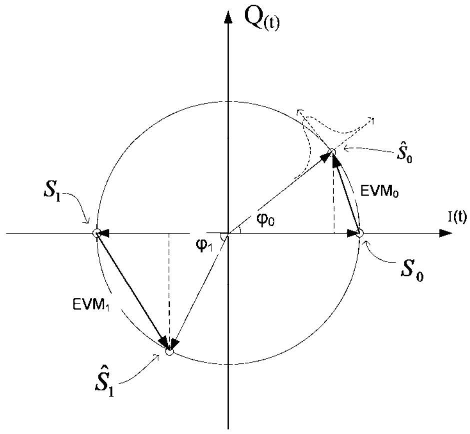

Fig. 11. Offset angle evaluation

At the Fig. 12 represented results of compensation algorithm working for the next parameters: REVM calculated on the 1024 bit frame and offset angle is 30 and 60 degrees. The dashed line shows BER dependence on E_b/N_o without offset, dot line sows BER with offset and full line shows result of compensation algorithm work.

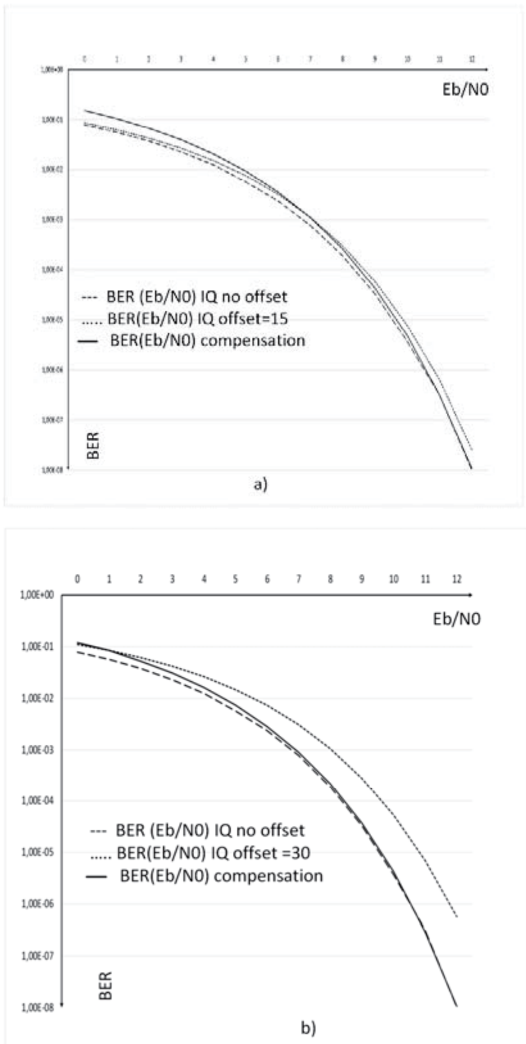

Fig. 12. Compensation algorithm results: a) offset 30˜, b) offset 60˜

So when E_b/N_o relation is low algorithm shows worsted results, because REVM cannot be correctly calculated. But we can evaluate E_b/N_o threshold for different offsets upper that algorithm will get excellence. This dependence represented at the Fig. 13.

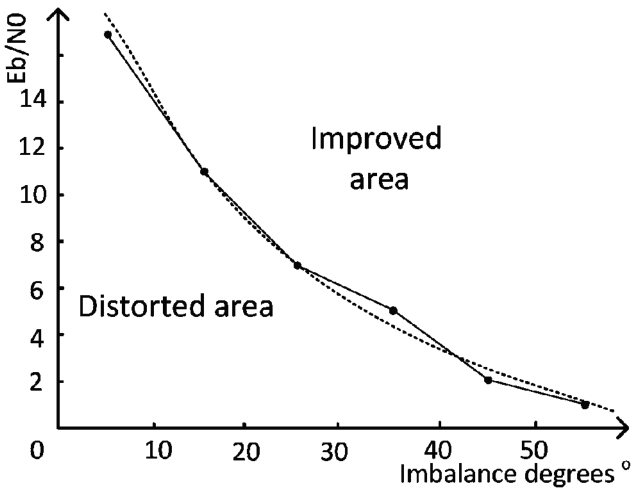

Fig. 13. Algorithm results for different offset values

So for better application this system we should exactly eliminate situation when there is an offset and E_b/N_o greater then threshold. Should be noted that analysis of reference sequences and modified RMER approaches can't eliminate these situations. At the Fig. 14 represented two BPSK signal constellations, the first has no offset a 7.6 dB of E_b/N_o ratio, the second have offset a 9.2 dB of E_b/N_o ratio. However, in these two cases, BER is equal $1.9*10^{-4}$.

For the differentiation of these cases, we will separate received REVM values of received symbols that was stored in a buffer for the intervals. This intervals evaluated for each data array with using Sterdges criterion[7]:

$$l = \frac{\overline{REVM}_{\max} - \overline{REVM}_{\min}}{1 + \log_2(k)}, \tag{16}$$

where $REVM_{min}$ and $REVM_{max}$ are maximal and minimal values of the received EVM, and k is buffer length. At the next, step the number of symbols for the each interval will be calculated, the limits of each Li represented by next formula:

$$L_i = \{\overline{REVM}_{\min} + li; \overline{REVM}_{\min} + l(i+1)\}. \tag{17}$$

At the Fig. 15 represented on of analyzed frame and its signal constellation, at the histogram horizontal ax shows the $REVM$ value related to the $\sqrt{\bar{E}_s}$ as 100% , vertical axe represents the number of symbols at the each interval L_i.

So when we have influence of high-level noise we will have dissipation for the different interval without offset, but when we have an offset of constellation an E_b/N_o is high there is the strong offset of experimental separation function and small dispersion. Let's consider the case of this algorithm working.

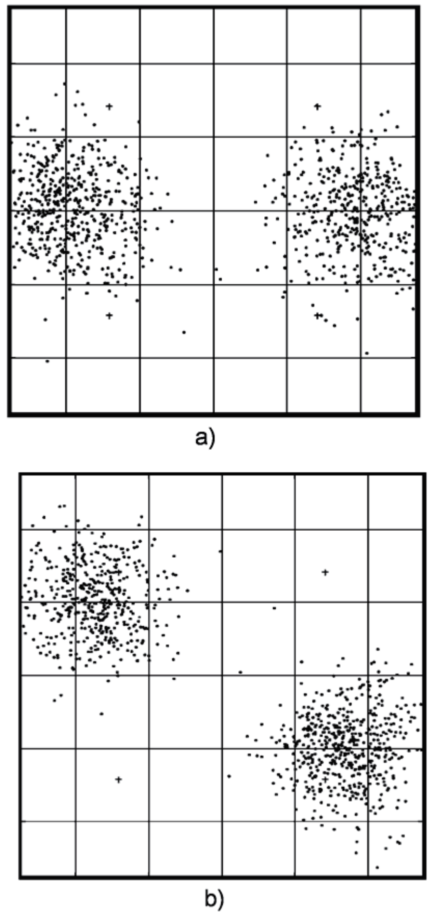

Fig. 14. Constellations with equal BER: a) without distortion, b) with distortion

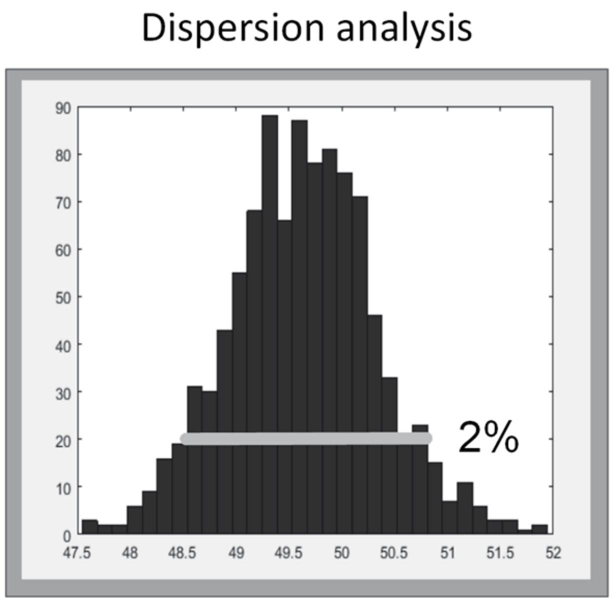

Fig. 15. Offset factor analysis

At the Fig. 16 represented working diagram of the algorithm with next set of parameters. The signal recognizes as distorted when dissipation overload 2%. Required BER is 10^{-5}. Each REVM calculated by averaging 1024 channel symbols, and for distortion evaluation analyzed 1000 frames.

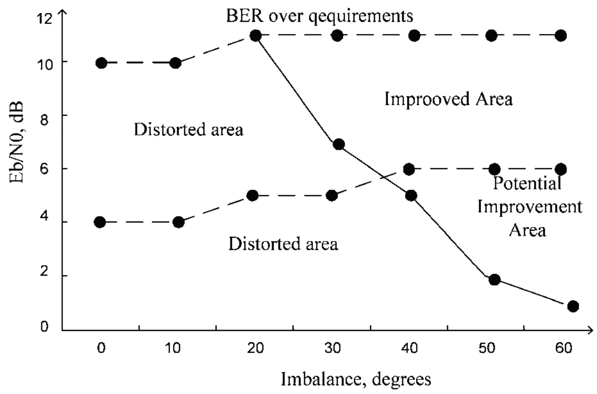

Fig. 16. Algorithm working diagram

VII. Conclusion

RMER based signal to noise ratio evaluation method proposed. It was established that there is a one-to-one dependence between RMER value and true SNR value for different modulation types. This approach allows spreading measurement band of measurement equipment. Signal constellation offset elimination algorithm based on non-reference metric REVM for BPSK signal proposed. This algorithm allows separating influence of AVGN and constellation offset.

Acknowledgment

This work was supported by RFBR grants (№ 16-37-00308).

References

[1] P.B. Kenington, *RF and Baseband Techniques for Software Defined Radio.* Artech House, 2005.

[2] W. Tuttlebee, *Software Defined Radio.* Edited by John Wiley & Sons, Ltd, 2002.

[3] Gu Qizheng, *RF System Design of Transceivers for Wireless Communications.* Springer, 2005.

[4] B. Sklar, *Digital communications: fundamentals and applications.* Prentice-Hall PTR, 2001.

[5] A. Goldsmith, *Wireless communications.* Stanford University, 2004.

[6] M. Zivkovic and R. Mathar, *Preamble-based SNR estimation in frequency selective channels for wireless OFDM systems.* In IEEE VTC 2009, 2009.

[7] C.R. Rao, *Handbook of statistics.* Vol. 24. Data mining and data visualization. ELSEVIER B.V., 2005.

[8] R. Schmogrow, B. Nebendahl, M. Winter, A. Josten, D. Hillerkuss, S.Koenig, J. Meyer, M. Dreschmann, M. Huebner, C. Koos, J. Becker, W. Freude, and J. Leuthold, “Error vector magnitude as a performance measure for advanced modulation formats”, *Photonics Technology Letters, IEEE*, vol.24(1), Jan 2012, pp. 61–63.

[9] A. Georgiadis, “Gain, phase imbalance, and phase noise effects on error vector magnitude”, *IEEE Transactions on Vehicular Technology*, vol.53(2), 2004, pp. 443–449.

[10] Digital Transmission: Carrier-to-Noise Ratio, Signal-to-Noise Ratio, and Modulation Error Ratio. White Paper, Cisco, 2006.

[11] CR1200R Digital Signal Analyzer Reference manual Web: https://accusrc.com/uploads/datasheets/7204_HukkCR1200R.pdf

[12] V. Mathuranathan, *Simulation of Digital Communication Systems Using Matlab.* Second edition. E-book. Smashwords, 2013.

[13] H. Arslan, H.A. Mahmoud, “Error Vector Magnitude to SNR Conversion for Nondata-Aided Receivers”, *IEEE Transactions on Wireless Communications,* vol.10, No.8, May 2009, pp. 2694-2704.

[14] Harry Y-F. Lam, *Analog and digital filters: design and realization.* Prentice-Hall PTR, 1979.

[15] C.M. Chile, “Bounds and Approximations for Rapid Evaluation of Coherent MPSK Error Probabilities”, *IEEE Trans. Commun.*, vol.33, March 1985, pp. 271–273.

[16] Umar H. Rizvi, Gerard J. M. Janssen and Jos H. Weber, “BER Analysis of BPSK and QPSK Constellations in the Presence of ADC Quantization Noise”, *in Proc. of APCC2008*, Kioto, Japan, 2008, IEICE 08 SB 0083.

[17] A. Amin, “Computation of Bit-Error Rate of Coherent and Non-Coherent Detection M-Ary PSK With Gray Code in BFWA Systems”, *International Journal of Advancements in Computing Technology*, vol.3, No.1, February 2011.

[18] M.D. McKinley, “EVM Calculation for Broadband Modulated Signals”, *in Proc. 64th ARFTG Conf. Dig.*, Orlando, Florida, 2004, pp. 45–52.

[19] R. Hassun, M. Flaherty, R. Matreci, and M. Taylor, “Effective evaluation of link quality using error vector magnitude techniques”, *in Proc. Wireless Communications Conference*, 1997.

[20] T.L. Jensen, T. Larsen, “Robust Computation of Error Vector Magnitude for Wireless Standards”, *IEEE Trans. Commun.*, vol.61(2), pp. 648–657.