Experimental Study of Cooperative MIMO at HF Band

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***Abstract*—Results of an experiment, on which base a capacity estimation of cooperative 2x2 MIMO, MISO, and SIMO was obtained for high frequency radio channels for the following cases: 1) presence of the channel state information on the receiving side only, 2) presence of the channel state information on both receiving and transmitting side, 3) incomplete and/or inaccurate channel state information on the transmitting side. The experiment was carried out under typical for the real use conditions of time and frequency synchronization of the radio, connected to each antenna element.**

***Keywords*—Cooperative MIMO, HF Communication System, MIMO System.**

I. Introduction

Technologies based on using Multiple-In-Multiple-Out (MIMO), in other words multiple antennas at both the transmitter and receiver are widely used in wireless communication systems of different frequency ranges. Historically they appeared as a development of receiving and transmit diversity methods, which were used for the first time in high frequency (HF) range and were evolving on the base of theoretical backlog, which has been created for this type of radio communication.

Currently technologies of wireless networks are far ahead of HF communication systems in the scale. Contrary to some predictions, the latter haven't disappeared at all, but have filled their own, smaller than it used to be, but still important niche, and continue evolving quite intensively. Thus, the opposite process of accommodation of technical solutions from the area of wireless communication systems to the HF area is possible, but the specificity of HF range should be taken into account.

There are relatively few papers devoted to the use of the multi-antenna technology in HF channels [1,2]. The majority of them are devoted to the use of MIMO, based on the polarization diversity of the received signal. Reportedly, in the accessible literature there is no information about the possibility of use of cooperative MIMO in HF channels.

It is traditionally considered that MIMO technologies can't provide significant improvement of HF communication channel characteristics because of: 1) HF channel has a clearly defined direction: radio paths usually have very big length and signal dispersion takes place in a small angular domain. 2) For a visible decorrelation of received signal by each antenna, antennas with big geometrical size are needed. 3) Low value of a signal-to-noise ratio (SNR) complicates the estimation of a channel matrix even on the receiving side. 4) Using HF channels as a feedback channel, transmission of channel state information from receiving side to the transmitting side is carried out with a big time delay and with a rough quantization, because of a relatively low transmission rate in a communication channel. It decreases the efficiency of use of the precoding methods on the transmission side. 5) The channel is almost always a multipath and frequency selective. A big delay interval between beams of the received signal does not permit the use of optimal algorithms of time-domain equalization even of Single-In-Single-Out (SISO) channel because of the exponential dependency of their complexity on the delay. The necessity of an additional use of space equalization algorithms for MIMO causes even bigger deviation from the use of optimal receiving procedures.

The only realizable benefit of MIMO in HF is the use of the relatively low transmission speed (hundreds of bits per second – units of Kbit/s) and relatively narrow frequency bands (hundreds of Hz – units of kHz), taken up by the signal. That is why sometimes in HF channel can be realized some of more effective (more optimal) and computationally complex algorithms of generation and processing of the signal, which are inapplicable in radio connection systems of another frequency ranges.

However, it is possible to overcome the first two most significant disadvantages by the use of cooperative MIMO in HF radio connection. It includes following methods:1) based on the use of retranslation of messages and 2) on merge of the group/groups of closely set correspondents for formation of the virtual receiving and transmitting antenna array. An option of cooperative MIMO in HF range based on the use of retranslation was described in [3]. This paper will consider the second option of cooperative MIMO.

II. Problem situation and goals

The task of providing the communication in HF channel between two groups of remote correspondents is considered. Each member from each group has its own station of HF connection. The distance between two groups of correspondents is much bigger than the maximum distance between members of the group, but the latter can be much bigger than used wave length. Coherence of reference generators of correspondent is missing. Correspondents of groups are connected between each other by high-speed communication channels (not HF but Wi-Fi, for example), which allow methods of combined generation/processing of transmitted/received signal. The connection is implemented

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only between two correspondents from two groups. Radio equipment of other group's members, which take part in the information exchange and which are neither the source, nor receivers of messages, but they perform an auxiliary role. I.e. the task of increasing data transmission speed and communication reliability at the expense of the use of cooperative MIMO methods not for the communication network but for one communication line point-to-point, is considered.

The goal was an estimation of the efficiency (from the point of view of information transmission) of cooperative MIMO communication channel in HF range on the base of direct measurement of channel matrix elements.

III. The description of conditions and methodology of experimentation

In this experiment two transmitters with capacity 100 W were involved, located in Voronezh (51.40N, 39.10E, Russia) and separated on a distance 8,2 km. Transmitters were working on whip antenna of length 6 m (in the majority of experiments) and on directional antennas of different types.

Receivers were located in Rjazan (54.63N, 39.73E, Russia) and were separated on a distance up to 15 km. The length of the radio path was about 330 km. For the receiving were used only whip antennas of length 6 m.

The testing was implemented in September 2012 in conditions of quiescent state of the middle-latitude ionosphere. In the majority of communication sessions were observed two signal beams: 1E and 1F2. One beam (1F2) condition – only at operation on frequencies higher than 12 MHz. The delay between beams was 1.4 up to 2.5 milliseconds. Always took place quick interference dying down of each beam: by Rayleigh and more seldom by Ricean (only in low frequency band < 4 MHz) law. Beams are uncorrelated.

Frequencies for the operation were chosen not only optimal at passing conditions but also lying lower than the estimated value of the optimal work frequency, for the purpose of work in conditions of more evident multipath effect, which are close to the maximum applicable frequency – for the purpose of analyzing of one-beam mode.

The duration of one communication session was varying from 5 to 15 minutes. The total cumulative duration of all communication sessions was about 15 hours.

Quadrature phase-shift keying (QPSK) signal was radiated in the frequency band 3100 Hz with manipulation speed 1200 – 3100 baud.

The signal received was carried out at deactivation of automatic gain control (AGC) mode and specially selected attenuator on the input of the receiver capacity amplifier for providing sufficient dynamic range, which guarantees the acceptable level of nonlinear distortions.

Those signals, for which this condition was not fulfilled, were excluded from the processing. For separation of signals from different transmitters was used a method of enlarging a spectrum of the signal being transmitted with a help of M-sequence or the sequence of Zadoff-Chu of length 31 up to 511 symbols. The choice of the length was made by criterion of the highest accuracy of measurements on the assumption of measured values of Doppler dispersion and the SNR. Every receiver was receiving mix of signals from each transmitter. In real time, by means of the matched filtering, the response signal was generated for each of the transmitted signals. This signal and the input base band signal of the receiver were written on the hard disk simultaneously for the purpose of the following processing in not real time.

We will examine the case of 2 receivers. It is more interesting practically, requires much less calculation and is easier for analysis, because the virtual two-element antenna always can be considered as uniform linear array (ULA), unlike the case of 3 and more correspondents, which will not be necessary located on equal distance along the line.

IV. Specifics of cooperative MIMO in HF range

There are clearly defined dying down of different speed in the channel. Fast fading has an interference nature. Slow fading is caused by other multiple reasons. Dynamic range of the slow fading exceeds the dynamic range of fast fading.

Usually during calculation of the interference immunity of SISO, Single-In-Multiple-Out (SIMO) and Multiple-In-Single-Out (MISO) systems of HF communication, slow fading of not interference nature is not taken into account, because it can be considered in the mean value of received signal capacity , and its correlation in space is high within the area, which is usually occupied by an antenna. i.e. the slow fading is considered as demonstration of non-stationary channel.

However, it is obvious that in the case of cooperative MIMO with a considerable separation of elements of a virtual MIMO antenna, the last condition will not be always fulfilled. Decorrelation of fast fading will be definitely implemented because of the separation on a distance which exceeds the wave length.

It is often considered that the only interest for the analysis of MIMO characteristics is correlation level of signals received by antenna elements and correlation level of interference, which also should have influence on the receiving accuracy. With a help of estimation of correlation matrix $\mathbf{R}$ it is possible to calculate many rates using either of channel model. But the majority, or almost all, models of MIMO channels were obtained for a description of wireless or cellular communication channels with higher frequency ranges than HF, and in consideration of the considerable specifics of the latter, calculation of MIMO communication channel parameters, based not on some analytical channel model but with a help of measured values of channel matrix $\mathbf{H}$, is of an interest;

There are approaches, which allow to calculate a correlation matrix of signal levels, spatially dispersed antenna elements subject to slow fading [4]. This result can be used for the calculation of characteristics of MIMO communication system (capacity, etc.) with a help of either model of MIMO communication channel. But some physical specifics of propagation environment of the signal in HF channel allow to assume the possibility of occurrence of such effects as keyhole or pinhole, which lead to the decrease of channel matrix rank and therefore to the visible decrease of MIMO technology effectiveness. These effects do not have an influence on the type of correlation matrix of MIMO channel and, therefore, will not have an influence on the result of calculation of communication channel parameters with its help. This is one more reason why it is advisable to perform a calculation of parameters of HF communication system with cooperative MIMO directly on the base of measured values $\mathbf{H}$, and not with a help of estimation $\mathbf{R}$.

V. Selection of quality indicators of HF communication system with cooperative MIMO

A standard quality indicator of MIMO systems is a capacity – ergodic or with a given probability of connection interruption for stationary and non-stationary channels, respectively. Unlike wireless communication systems (information transmission speed there almost reaches the capacity), for HF channel this quality indicator is not so useful from the practical point of view. The reason is that in HF channel the gap between actual realizable speed of information transmission and its capacity is much bigger than in communication systems with higher frequency range because of the smaller values of signal/noise ratio and frequency selectivity of HF communication channel.

But this criterion is of a big theoretical interest, as the upper limit of date transmission speed. From a practical point of view it is advisable to supplement it with a criterion that gives the lower border of data transmission speed. As such criterion was chosen a criterion of minimization of bit error rate (BER), giving the data transmission speed, calculated as:

$$C = v\left[\log m + p\log_2 p/(m-1) + (1-p)\log_2(1-p)\right] \quad (1)$$

where v - technical speed of data transmission, m - degree of modulation, p - symbolic error probability, monotonous depending on BER.

The last criterion is not universal because it should take into account many different factors: modulation type (phase-shift keying (PSK), quadrature amplitude modulation (QAM)) and its degree, method of dealing with multipath effect (Orthogonal frequency-division multiplexing (OFDM) or any equalizer type in time domain), channel estimation method, etc. Calculation of minimal BER by optimization of parameters of MIMO communication system in the dying down channel, can be done only numerically. The capacity analytical expressions are known. In this paper for estimation of efficiency of cooperative MIMO in HF range we will use both indicators. At BER minimization, as a method of processing we will use classic versions of receiving OFDM according to [5].

VI. Post-Processing methodology

Processing of measurement results not in real time was implemented in MATLAB. Preprocessing was made up of correction of frequency mismatch, implemented with a help of analysis of signal spectrogram.

In the future, signal mode structure estimation was implemented for each of 4 communication subchannels with a help of the spectrogram analysis, notably complex amplitudes of interfering beams and mutual delays between them. Delays between beams within one communication session were considered to be permanent, which follows from the physical model of the communication channel and conforms to the data of the experiment. Calculation of all those parameters was implemented by standard methods of optimal filtration by criteria of mean square error minimum.

As the measurement of multidimensional HF channel characteristics (elements of channel matrix **H**) is implemented at relatively low level of signal-to-noise ratio (in contrast to cellular communication and ultra high frequency (UHF) wireless systems), the measurement errors can affect the value of estimated capacity.

At a modeling stage of channel capacity calculation it is shown, that substitution of inaccurate (noise admixed) values into channel matrix **H** instead of precise values leads to increase of calculated MIMO channel capacity value. This effect can be intuitively explained by reduction in correlation between elements of **H**. Consequently, it is necessary to develop methods for statistical processing of measurement results, for accuracy estimation of calculated MIMO-channel capacity value.

This task is represented in [6] for the channels with flat fading, while the HF channel is inclined to frequency-selective fading. Formulas given in [6] for calculation of channel capacity in basis of inaccurate MIMO-channel characteristics measurement are represented for various error-models and various channel state information inaccuracy. The availability of measurement-error correlation matrix allows to provide the capacity value estimation using minimum mean square error (MMSE) criterion, whereas in case of unavailable measurement-error correlation matrix simple least squares (LS) method can be used.

Channel matrix estimation in papers above is implemented using channel test procedure with signal, similar to that used in real communication, in state of synchronization between transmitted sequences and coherence of transmitters' local oscillators. These conditions are not provided in experiment presented in this paper. It should be taken into account in the channel capacity calculation method.

Let's develop methods of capacity estimation utilizing inaccurate measurement results. If the L-beam wideband MIMO channel is discussed, received signal as the $n_{Tx} \times n_{PSP}$ matrix of temporal samples is represented as:

$$\mathbf{Y}(t) = \sum_{i=0}^{L-1} \mathbf{H}_i(t)\mathbf{X}(t-\tau_i) + \mathbf{N}(t), \quad (2)$$

where $\mathbf{X}(t)$ is $n_{Tx} \times n_{PSP}$ matrix of complex samples transmitted at an instant time t . τ_i is delay in beam with number i . $\mathbf{N}(t)$ is $n_{Tx} \times n_{PSP}$ matrix of noise samples at an instant time t . An input of each receiver is equipped with the set of n_{Tx} filters, matched to the transmitted signals. Maximum output signal (on time interval equal to test sequence duration) of the i -th receiver's j -th filter if proportional to the channel transmission ratio h_{ij} , if noise and interference between transmitted signals are neglected.

Matrix $\mathbf{X}(t)$ is not perfectly known at the transmitter and receiver. It is just considered to consist of cyclically shifted rows, each contains test sequence from the corresponding transmitter. The circular shift is due to incoherence of transmitters' local oscillators and to the various signal propagation delays.

Assume, the MIMO channel state is constant at a time interval equal to test sequence duration n_{PSP}. It is provided by choice of test sequence length based on preliminary estimation of time coherence. Then elements of the channel matrix for each beam can be defined from values of matched filters' output signals. A peak signal corresponds to a strongest beam, a second-large peak corresponds to second beam etc. A peak-to-peak time interval corresponds to delay between beams. The delay relied constant during all session that allowed averaging. The last assumption is based on physical model of the channel, affirmed numerous experimental data.

Let's denote a matrix of matched filters' output signals as $\tilde{\mathbf{Y}}_i$ for i-th beam. Then LS estimate of i-th beam channel matrix is:

$$\hat{\mathbf{H}}_i^{(LS)} = \mathbf{Y}\mathbf{X}^H\left(\mathbf{X}\mathbf{X}^H\right)^{-1}. \quad (3)$$

If Zadoff-Chu sequences are used, it can be solved as $\mathbf{X}\mathbf{X}^H = \left(P/n_{Tx}\right)\mathbf{I}$ and minimal square error (MSE):

$$MSE_{LS} = \left(n_{Tx}^2 n_{Rx}\right)/\rho\,. \quad (4)$$

If the channel correlation matrix is available, the MMSE estimate of channel matrix is:

$$\hat{\mathbf{H}}_i^{(MMSE)} = \tilde{\mathbf{Y}}_i\left(\mathbf{X}\mathbf{R}_H\mathbf{X} - \sigma_n^2 n_{Rx}\mathbf{I}\right)^{-1}\mathbf{X}\mathbf{R}_H \quad (5)$$

$$MSE_{MMSE} = tr\left\{\left(R_H^{-1} + \left(HH^H\right)/\left(\sigma_n^2 n_{Rx}\right)\right)^{-1}\right\}. \quad (6)$$

As these quantities are calculated, the MMSE estimate of instant capacity can be found [7]:

$$\hat{C} = \log_2\left[\det\left(\mathbf{I} + \left(\rho/n_{Rx}\right)\hat{\mathbf{H}}\hat{\mathbf{H}}^H/\left(1+\rho MSE/\left(n_{Rx}n_{Tx}\right)\right)\right)\right]. \quad (7)$$

VII. Calculation of Parameters

A. Perfect CSIR no CSIT

When there is channel state information on receiving side (CSIR) and no channel state information on the transmission side (CSIT), the capacity is equally distributed between eigen subchannels on the transmission. A capacity for a non-selective channel for MIMO, SIMO/MISO, SISO cases is calculates according (1). In the case of frequency selective fading, on the basis of measured channel transmission coefficients of every i-th beam, which form the matrix $\mathbf{H}_i(t)$, and delays of each of beams $\tau_i(t)$, a transmission coefficient of every channel for every frequency is calculated in the form of matrix

$$\mathbf{H}(f,t) = \sum_{i=1}\mathbf{H}_i(t)e^{-j2\pi f\tau_i(t)} \quad (8)$$

for MIMO or vector

$$\mathbf{h}(t,f) = \sum\mathbf{h}_i(t)e^{j2\pi f\tau(t)} \quad (9)$$

for SIMO or MISO and then momentary value of the capacity

$$C(t) = \left(1/F\right)\int_F C(f,t)\,df\,. \quad (10)$$

Using the latter, it is easy to estimate the distribution law of the capacity, time mean value C – ergodic capacity and the specified probability ε of outage (supportable rate) $-\varepsilon$-distribution quantile C.

B. Perfect CSIR and perfect CSIT

For classic MIMO and single-beam communication channel, in case of presence of channel state information on the transmission side, the calculation of a capacity is not a problem. The distribution of the capacity on eigen subchannels, corresponding to right eigenvectors of a singular value decomposition (SVD) of a channel matrix $\mathbf{H}$ should be implemented under a well-known so called "waterfilling" principle, which provides the maximization of capacity value. In the case of cooperative MIMO the feature of capacity maximization consists in that instead of the limitation of a total radiation power of all antenna elements

$$\sum_{i=1}^{n_{Tx}} P_i \le P_\Sigma\,, \quad (11)$$

is used the limitation of a signal capacity, which is radiated by each single antenna element of the virtual transmission antenna array of all j-th subchannels, where

$$j \le r = rank(\mathbf{H}), \quad (12)$$

the capacity of connected radio transmitter

$$\sum_{i=1}^{r} P_{ij} \le P_i\,, \quad (13)$$

i.e. arbitrary redistribution of total capacity between transmitters in the case of cooperative MIMO is impossible (unlike non-cooperative MIMO, which allows radiation of a total power even by one antenna element). With such constraints the task becomes classical task of a linear programming, which can be solved by standard abilities of MATLAB.

A bigger difficulty is taking into account of selective nature of fading in the channel, caused by multipath. Formally, from theoretical point of view, a capacity of frequency-selective channel in the case of exactly known transmission channel characteristics (and only in this case), is equal to the capacity of the non selective channel with a same signal/noise ratio. But practically, algorithm of receiving the information with a speed close to such capacity is impossible to realize, even for SISO communication systems because of the high computational complexity. That is why it is not interesting to use this indicator. And this is the reason why we will use the calculation of capacity in this case for the perspective algorithm of generation and processing of signals in MIMO communication system with frequency selective (wideband) channels.

For channels with flat fading, the receiving algorithm, which maximizes the capacity proposes: 1) diagonalization of the channel matrix $\mathbf{H}$ with a help of SVD decomposition, 2) decomposition of the channel into $r = rank(\mathbf{H})$ independent subchannels and 3) optimal decomposition of capacity of each transmitter P_i ($i = 1 \ldots n_{Tx}$) between r subchannels with the above-mentioned limitations. However, frequency-selective channel is described not by the channel matrix of scalar type $\mathbf{H}$, but by the matrix of its impulse responses. When describing the channel in such form, the received signal is presented in the form of convolution. The usual version of channel description

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \tag{14}$$

can be obtained for z-images of received and transmitted signals, at description of MIMO channel by polynomial matrix of z-images of its impulse responses $\mathbf{H}(z)$ (z-transformation transforms convolution into a product:

$$\mathbf{y}(z) = \mathbf{H}(z)\mathbf{x}(z) + \mathbf{n}(z)). \tag{15}$$

If with a help of polynomial SVD (PSVD) [8] is implemented diagonalization

$$\mathbf{H}(z) = \mathbf{U}(z)\mathbf{\Sigma}(z)\tilde{\mathbf{V}}(z) \tag{16}$$

(The sign "tilde" indicates para-Hermitian conjugation:

$$\tilde{\mathbf{H}}(z) = \mathbf{H}^T\left(z^{-*}\right), \tag{17}$$

i.e. transposition, complex conjugation of polynomial coefficients and change of the sign of the exponent for each z), frequency-selective MIMO channel is transformed into the summation of independent frequency-selective channels with c z-transmission functions in the form of elements of a diagonal polynomial matrix of singular values

$$\mathbf{\Sigma}(z) = diag\left(\sigma_1(z),\ \ldots, \sigma_r(z)\right). \tag{18}$$

Then it is not difficult to calculate the frequency transmission function of each of subchannels $\sigma\left(z = e^{j2\pi f}\right)$ and to calculate the error probability in every subchannel as:

$$p_i\left(P_i\right) = \int p\left(\sigma_i(f)\sum_j^{n_{Tx}} \rho_{ij}\right) df . \tag{19}$$

Using the last expression it is possible to obtain numerically the capacity decomposition at eigen subchannels, which minimizes BER (it is equal to the minimization $\sum_{i=1}^{r} p_i$).

VIII. COMPUTATION RESULTS

As a result of experimental date processing was obtained the capacity of communication channel for SISO and cooperative versions of SIMO (distributed receiving), MISO (distributed transmission), MIMO.

Typical examples of their histograms C are described in fig. 1. Ergodic capacity dependencies are described in fig. 2. Typical examples of channel matrix $\mathbf{H}$ eigenvalues histograms are described in fig. 3.

Mentioned correspond to the typical communication channel state: two beams of almost equal capacity, with the delay about 1 millisecond and with Doppler 0.5 uo to 1 Hz.

It is known, that for SISO communication systems the frequency- selective fading does not magnify ergodic capacity. But in [9] is theoretically shown, that the frequency selectivity magnifies ergodic transmission capacity of MIMO communication systems.

As a result of the carried out measurements has appeared, that though in the considered task the given scoring not so significant as was predicted theoretically in [9], but it actually takes place.

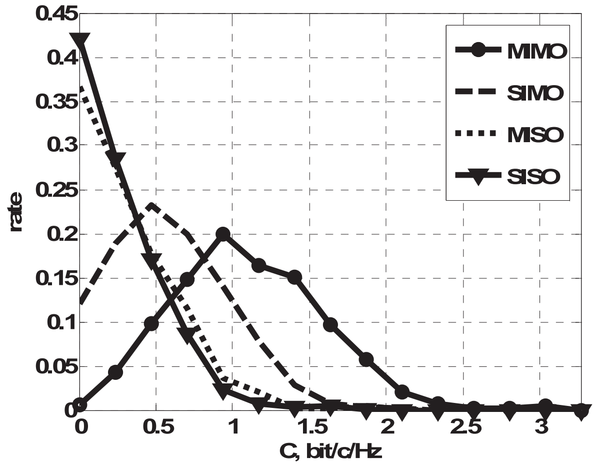

Fig. 1. Histograms of the capacity with $\rho = 15$ dB

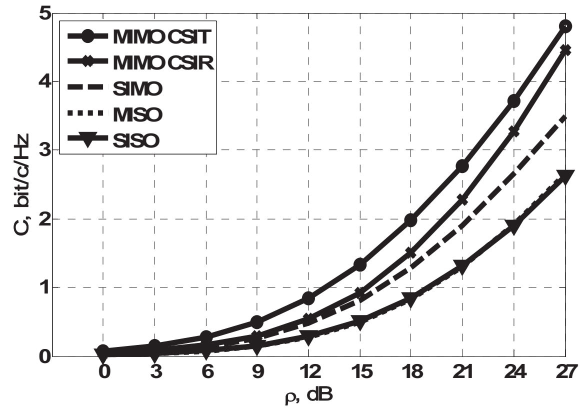

Fig. 2. Dependency of the ergodic capacity SNR

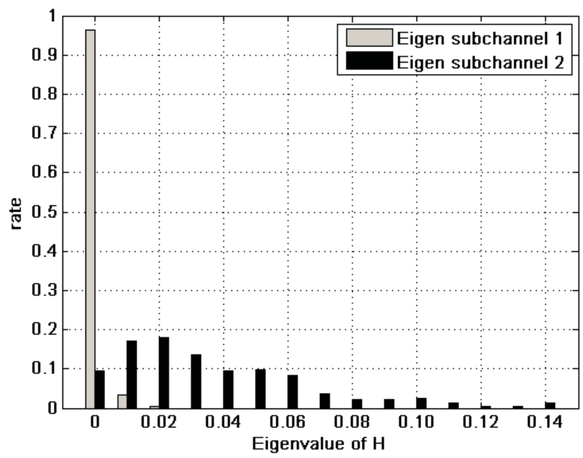

Fig. 3. Channel matrix H eigenvalues histogram.

It is known also, that the frequency selectivity should magnify transmission capacity with preset probability of an outage [10]. It is correct both for MIMO, and SIMO communication systems. It is due to effect of an additional diversity by multipath propagation. The carried out measurements confirm above mentioned conclusion for the variant of cooperative MIMO described in this paper.

IX. CONCLUSIONS

As a result of experimental data processing, on the basis of direct measurement of channel matrix elements, HF range cooperative MIMO channel capacity characteristics were obtained, as well as cooperative SIMO, MISO and usual SISO channels' capacity characteristics.

A comparison of their numerical values indicates the possibility of a significant increase of the information transmission rate due to the use of cooperative MIMO. Because of the steep dependence of C from SNR, the value of the energy gain may seen insignificant, but in the whole interested SNR range the increase of MIMO transmission speed in comparison with the SIMO is measures in kilobits per second, even in 3100 Hz channel band.

Even though the calculation of capacity with a given form of the signal and processing method demonstrates its appreciably smaller value, compared to the Shannon capacity, obtained on the basis of calculation of mutual information, it doesn't change qualitative conclusions, which follow from the comparative analysis of results relative to effectiveness of cooperative MIMO in HF channel.

Thus, obtained results indicate the promising prospects for cooperative MIMO technologies in HF range radio communication systems of the concerned type.

REFERENCES

[1] S. D. Gunashekar, E. M. Warrington, S. Salous, S. M. Feeney, N. M. Abbasi, L. Bertel, D. Lemur, and M. Oger, "Investigations into the feasibility of multiple input multiple output techniques within the HF band: Preliminary results," *Radio Sci*., 44, RS0A19, 2009

[2] Nasir Mehmood Abbasi. "An experimental investigation into the feasibility of MIMO techniques within the HF band" PhD Thesis. Department of Engineering, University of Leicester, August 2011

[3] H.J. Strangeways, "Estimation of signal correlation at spaced antennas for multi-moded ionospherically reflected signals and its effect on the capacity of SIMO and MIMO HF links," *The IET 10th International Conference on Ionospheric Radio Systems and Techniques*, London, UK, 2007, pp. 306 - 310.

[4] Yu. B. Nechaev, A. A. Malyutin, I. O. Dvorgakova, P. N. Rad'ko, "Manipulation codes decision for communication systems with trans-modulation using the concept of cooperative MIMO," in *Proc. 13th International Conference "Digital Signal Processing – DSPA-2011"*, Moscow, Russia, 2011, pp.49 - 51.

[5] MIL-STD-188-110C, United States Military Standard, 2011

[6] T. Yoo and A.Goldsmith, "Capacity of Fading MIMO Channels with Channel Estimation Error", in *IEEE International Conference on Communications*, vol. 2, 20-24 June 2004, pp. 808 – 813.

[7] M. Biguesh and A. B. Gershman, "Training-based MIMO channel estimation: a study of estimator tradeoffs and optimal training signals," in *IEEE Trans. Signal Proc.*, vol. 54, No. 3, Mar. 2006, pp. 884 – 893.

[8] I. O. Dvorakova, V. A. Makovy, A. A. Malyutin and Yu. B. Nechaev, "Matrix Decompositions for Precoding and Equalization of MIMO Channel with ISI," in *Proc. 35th International Conf. on Telecommunications and Signal Processing (TSP)*, Prague, Czech Republic, July 3-4, 2012, pp. 132 - 135

[9] D. Gesbert, H. Bolcskei, D. Gore, and A. J. Paulraj, "MIMO wireless channels: Capacity and performance prediction," in *Proc. Globecomm 2000*, San Francisco, CA, 2000, pp. 1083 – 1088.

[10] A. F. Molisch, M. Steinbauer, M. Toeltsch, E. Bonek and R. S. Thomä "Capacity of MIMO Systems Based on Measured Wireless Channels," *IEEE Journal on Selected Areas in Commun.,* vol. 20, No 3, Apr. 2002, pp. 561 - 569.