CAPACITY ESTIMATION OF HF-MIMO SYSTEMS

N. Abbasi[1] (nma12@le.ac.uk), **S.D. Gunashekar**[1], **E.M. Warrington**[1], **S. Salous**[2], **S. Feeney**[2], **L. Bertel**[3], **D. Lemur**[3] **and M. Oger**[3]

[1] Department of Engineering, University of Leicester, Leicester LE1 7RH, U.K.
[2] School of Engineering, Durham University, DH1 3LE, U.K.
[3] IETR, UMR 6164, Université de Rennes 1, Rennes, France

Keywords: HF-MIMO, collocated antennas.

Abstract

Multiple input multiple output (MIMO) systems utilize multiple antennas at both the transmitter and the receiver. This paper describes some recent experimental work that has been carried out in order to investigate the feasibility of applying MIMO techniques within the high frequency (HF) band. It is a significant development because the potential increase in data rates will benefit not only the existing HF radio systems but also open this band to new low cost communication applications. The capacity estimates for systems employing multiple antennas at the transmitter and receiver in the HF band are computed. Specifically a comparison is made between MIMO configurations employing homogenous antenna arrays and collocated antenna arrays in terms of their envelope correlation and capacity. The results indicate that the HF band can be used for MIMO applications and that compact collocated antennas can replace large homogenous arrays to provide potential capacity gains.

1 Introduction

MIMO communication systems increase data throughput using parallel data streams created by the multipath propagation of radio signals [3]. Although much research has been performed in the case of higher frequency bands (VHF/UHF/SHF), there has been very little research reported in literature to apply the concepts of MIMO to the HF band.

HF radio waves propagate between the transmitter and receiver via multiple paths arising from the reflection of radio waves from different layers of the ionosphere as well as multi-hop propagation [2]. In addition, HF waves split into the ordinary (O) and extraordinary (X) magneto-ionic components in the ionosphere. The existence of multipath propagation makes HF an ideal candidate for application of MIMO techniques. This however has its own challenges. The size of traditional spaced antenna arrays used at HF is large and consequently spaced arrays occupy considerable area eliminating it as an option for many applications. The approach of using collocated antenna however has the potential to overcome this barrier [1]. Thus, the MIMO related research advancements in the higher frequency bands cannot necessarily be directly applied to the HF band.

2 Experimental configuration

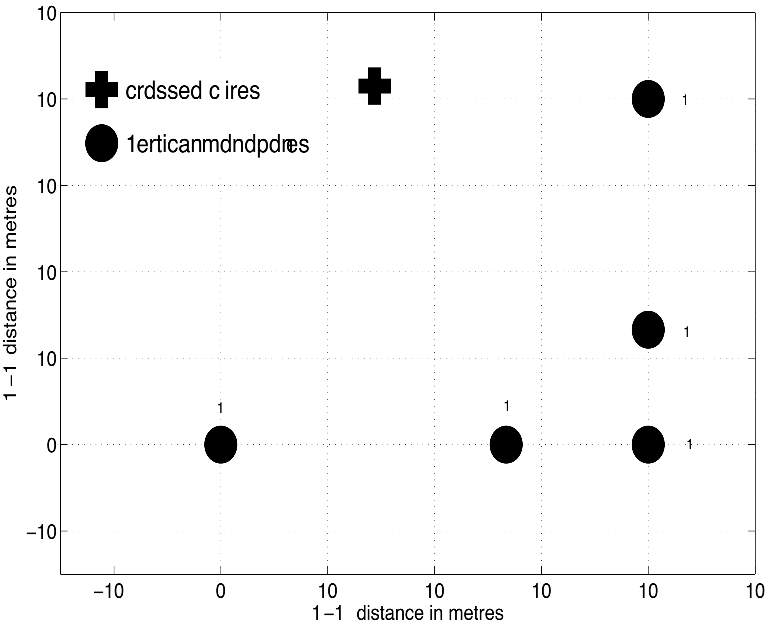

Figure 1: *The position of the L-shaped array of 5 monopoles and crossed inverted V antennas at Bruntingthorpe (near Leicester).*

For the results presented in this paper data from two communication links were analyzed: Durham-Bruntingthorpe (near Leicester) link of 255 km in the UK and Durham-Monterfil, France link of 743 km across the English channel.

Continuous wave transmissions between 4 and 10 MHz were used in various experiments conducted between September 2007 and December 2008. Currently the system has the capability of transmitting on up to 4 channels and receiving on up to 8 channels. The basic antenna configuration in Bruntingthorpe is comprised of an L-shaped spaced array of 5 monopole antennas with equidistant arms (40 m) facing North-South and East-West as shown in Figure 1. In addition other types of antennas such as inverted V wire and loop antennas were used to add antenna and polarization diversity. Similarly different types of antennas such as crossed wires, loop and vertical were also used at the transmitter.

3 Measurements

The following sub-sections describe some of the results obtained during two experimental campaigns conducted over the Durham-Leicester and Durham-Monterfil paths.

3.1 Durham-Leicester path

The first set of measurements was undertaken on 2 July 2008. The transmit array consisted of two collocated crossed wire inverted V antennas, a vertical antenna and a loop antenna while the receive array was comprised of two vertical antennas spaced 40 m apart (antennas 1 and 3 in Figure 1) and two crossed wires oriented in the N-S and E-W direction (location shown in Figure 1). Continuous wave transmissions at a nominal frequency of 5.255 MHz were used with a separation of 10 Hz at each transmit antenna. This separation was necessary to distinguish signals from different transmit antennas at the receiver. Data were collected between 10:02:46 UT to 11:53:01 UT in lengths of 60 s duration.

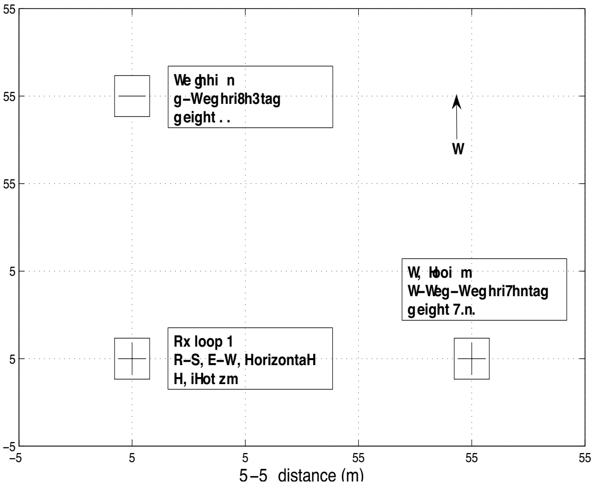

Figure 2: *The position of the L-shaped array of collocated antennas employed at Monterfil, France.*

3.2 Durham-Monterfil path

The second set of measurements was made on 3 September 2008 over a 743 km radio link between Durham, UK and Monterfil, France. Four transmit antennas and eight receive antennas were used (antenna configuration at the receiver is shown in Figure 2). The transmit array consisted of collocated North-South (Tx-1) and East-West (Tx-2) inverted V antennas and spaced (5 m apart) loops in S-E/N-W (Tx-3) and S-W/N-E (Tx-4) directions. The receive array consisted of three sets of collocated loop antennas arranged in an L-shaped configuration with a separation distance of 15 m (λ/4) as shown in the Figure 2. Receiver loop array 1 and 2 had three antennas each with E-W, N-S and horizontal configuration while loop array 3 had two antennas with E-W and horizontal configuration. Loops arrays 1, 2 and 3 were placed at heights of 7 m, 8.3 m and 2 m respectively above the ground level.

4.1 Results and discussion: Durham-Leicester path

For each transmitting antenna, histograms of envelope correlation coefficient between the spaced monopoles and crossed wires are shown Figures 3 and 4 respectively. The spaced monopole antennas show a high degree of correlation (almost all measurements lie between the correlation range of 0.5-1 with a majority of them having correlation coefficient very close to 1). This indicates that under the prevailing ionospheric conditions and a spacing of 40 m (0.7λ) the two antennas are highly correlated. In contrast, the collocated antennas show a significantly greater degree of decorrelation.

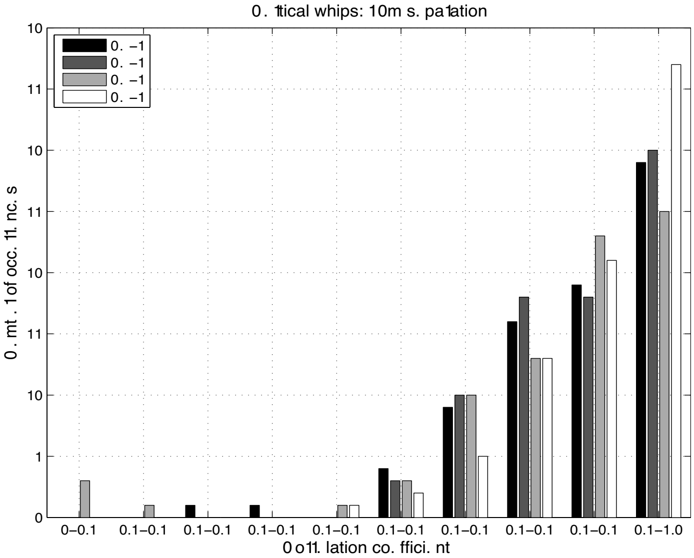

Figure 3: *Envelope correlation coefficients for signals received at two vertical monopoles spaced 40 m apart for four different transmit antennas. (2 July 2008).*

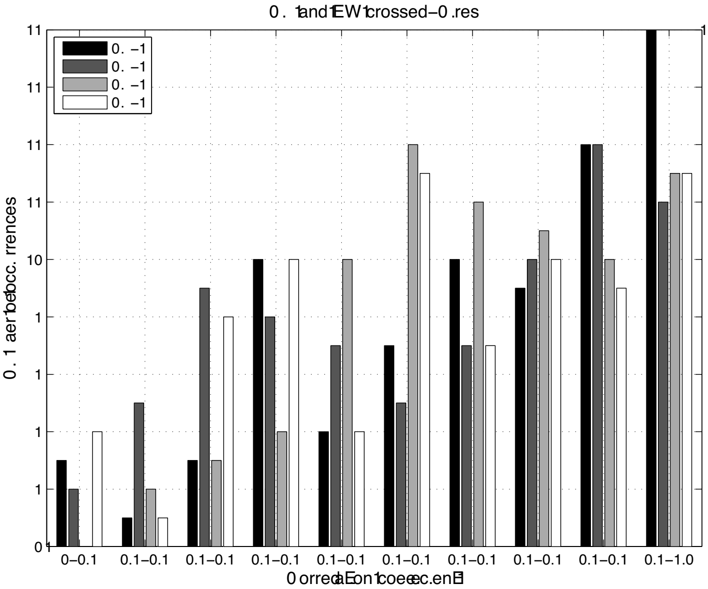

Figure 4: *Envelope correlation coefficients for signals received at two crossed wires for four different transmit antennas (2 July 2008).*

The ultimate objective of employing MIMO is to achieve higher data rates. Reduced correlation does not necessarily imply higher capacity [6] as degenerate channels have been observed at VHF/UHF frequencies which are uncorrelated but still do not offer any increase in capacity. This happens due to the keyhole effect, which reduces the degree of freedom of the channel to one. To verify that the decorrelation results in an increased throughput, average capacity of the channel was computed using thirty-four files of 1 minute duration using Equation 1.

$$C = \log_2(\det(\frac{\rho}{n_T} HH^H + I_{nR}) \quad bps/Hz \qquad (1)$$

where ρ is the signal to noise ratio, H is the measured channel matrix and H^H is the conjugate transpose of this matrix. The entries of the H matrix are calculated using the peaks of the fourier transform of the received signal. It is then normalized using the Frobenious norm to compensate for power fluctuations. The average capacity estimates calculated using Equation (1) for 2x2 and 3x3 MIMO configurations are shown in Figure 5 for SNR values up to 40 dB. The results shown in Figure 5 indicate a marked improvement in capacity as the number of transmitting and receiving antennas is increased.

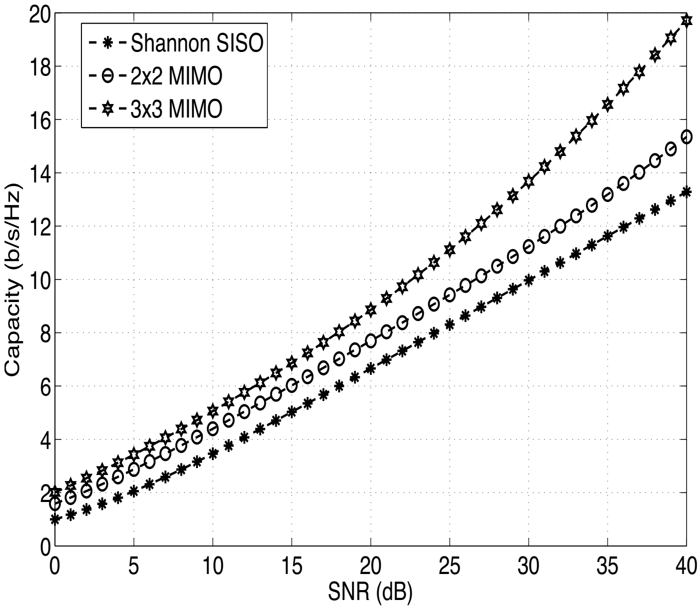

Figure 5: *Capacity estimates for 2x2 and 3x3 MIMO compared to the Shannon SISO capacity (2 July 2008).*

To compare the homogenous spaced array with the collocated antenna array the capacity estimates for a 2x2 vertical monopole configuration and 2x2 configuration employing crossed wire inverted V antennas at the receiver were computed. These were calculated for a SNR of 25 dB, which was the approximate average SNR for this campaign. The same two transmit antennas were used in both configurations. The results shown in Figure 6 indicate that the capacity for the 2x2 configuration that employed the crossed wires is always greater than that employing the vertical antennas at the receiver end, which corresponds to the lower correlation coefficient values for the crossed wires as compared to the spaced monopoles. In addition the capacity of the MIMO configuration using the spaced vertical antennas stays almost constant during the measurement period while the capacity values of the crossed wire array fluctuates (though it always remains higher than that of the monopoles).

4.2 Results and discussion: Durham-Monterfil path

The second campaign performed over the Durham-Monterfil path corroborated the results of the first experiment. The envelope correlation coefficient histograms for the various pairs of receive antennas corresponding to each transmitter is shown in Figure 7. The frequency histograms indicate that the antennas have low correlation values especially for the loop array 1. The collocated loop array 3 is highly correlated which can be attributed to the coupling of the two loops due to the small antenna height (2 m) above ground. On average an appreciable degree of decorrelation is achieved which is comparable to large homogenous spaced arrays. This confirms the results of previous studies [4,7]. The capacity results for this campaign are described in [5] where it has been shown that high relative capacity gains are achieved for 2x2, 3x3 and 4x4 MIMO. Also the capacity estimates for configurations involving spaced and collocated antennas were compared in [5] which were found to be similar to the results of Durham-Leicester path.

5 Concluding remarks

It has been shown that high capacity gains can be expected in the HF band using MIMO. The basic indicator of the successful implementation of MIMO is the degree of decorrelation achieved between signals transmitted and received at different antennas. This decorrelation depends on the prevailing ionospheric conditions and the design and placement of antennas. The degree of correlation obtained with homogenous arrays depends on the distance between the antenna elements in the array. Large antenna arrays would be required to achieve the expected capacity gains. The spaced homogenous arrays can be replaced by collocated antennas and heterogeneous arrays for achieving low correlation resulting in potential improvements in capacity.

Future work will involve the optimization of collocated antenna arrays for MIMO applications. Different types of collocated antennas will be used in heterogeneous configurations to allow space, antenna and polarization diversity to come into play at both the transmitter and receiver ends of the link.

Acknowledgement

The authors are grateful to the EPSRC for their financial support of this work. The collaboration between UK and French groups in this investigation is facilitated through the EU COST-296 Action on the Mitigation of Ionospheric Effects on Radio Systems (MIERS).

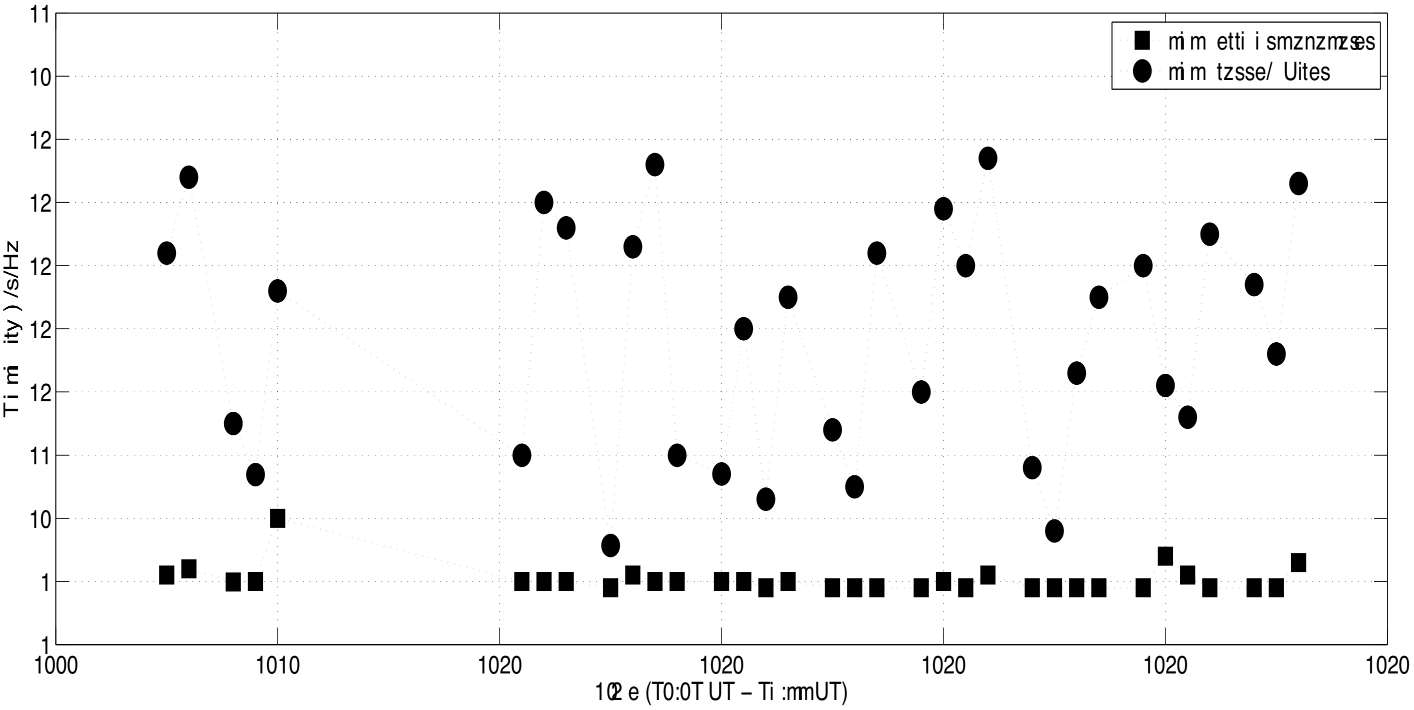

Figure 6: *Comparison of 2x2 MIMO capacities (between 1001 UT and 1056 UT on 2 July 2008 at an SNR of 25 dB).*

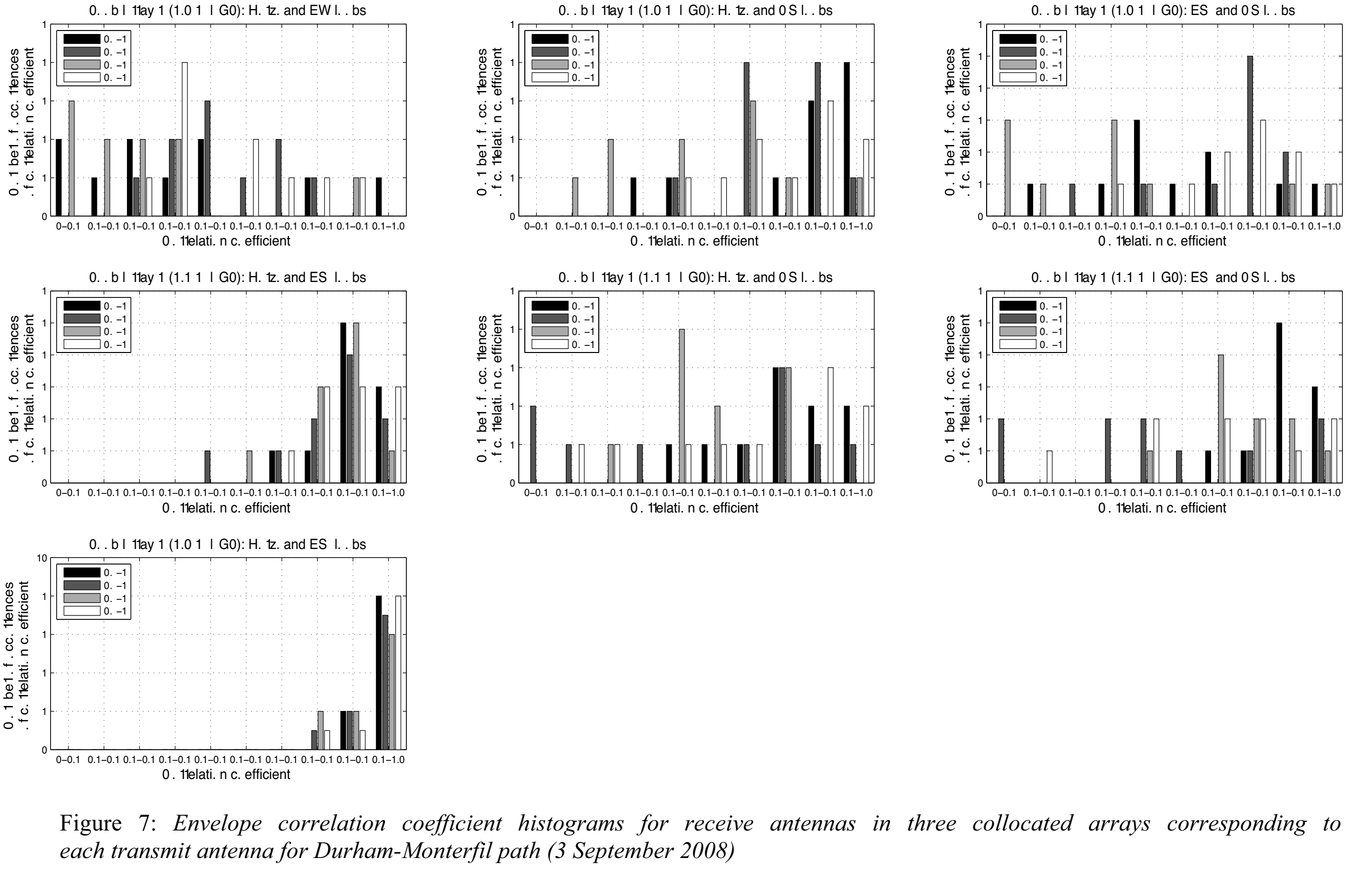

Figure 7: *Envelope correlation coefficient histograms for receive antennas in three collocated arrays corresponding to each transmit antenna for Durham-Monterfil path (3 September 2008)*

References

[1] A. Bisiaux and L. Bertel, "Antenna diversity as a means of improving HF transmissions", *Proceedings of the IEEE, HF Radio Systems and Technique,* Guildford, U.K, (2000).

[2] K. Davies, "Ionospheric Radio," *Peter Peregrinus Limited*, UK, (1990).

[3] G. J. Foschini and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas", *Wireless Personal Communications,* vol. 6, No. 3, pp. 311–335, (1998).

[4] S.D. Gunashekar, E.M. Warrington, S. Salous, S.M. Feeney, H. Zhang, N. Abbasi, L. Bertel, D. Lemur, and M. Oger, "Early Results of Experiments to Investigate the Feasibility of Employing MIMO Techniques in the HF Band", *Proceedings of the Loughborough Antennas and Propagation Conference*, Loughborough, UK, (2008).

[5] S.D. Gunashekar, E.M. Warrington, S. Salous, S.M. Feeney, N. Abbasi, L. Bertel, D. lemur and M. Oger, "The Use of Heterogeneous Antenna Arrays in Experimental HF-MIMO Links", *3rd European Conference on Antennas and Propagation*, Berlin, Germany (2009).

[6] S. Loyka and A. Kouki, "MIMO channel capacity, correlations and keyholes: Analysis of degenerate channels", *IEEE Transactions on Communications*, vol. 50, no. 12 (2002).

[7] E.M. Warrington, S.D. Gunashekar, S. Salous, S.M. Feeney, H. Zhang, N. Abbasi, L. Bertel, D. Lemur and M. Oger, "Investigations into the Feasibility of MIMO Techniques Within the HF Band: Preliminary Results", *12th International Ionospheric Effects Symposium*, Virginia, USA, (2008).