EXPERIMENTAL RESULTS ON MULTICARRIER SIMO HF COMMUNICATIONS

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Abstract

Achieving reliable communication over HF channels is known to be challenging due to the particularly hostile propagation medium. To address this problem, diversity techniques were shown to be promising. In this paper, we demonstrate through experimental results the benefits of different diversity strategies when applied to multi-input-multi-output (MIMO) multicarrier systems. The performance gains of polarisation, space and frequency diversities are quantified using different measurement campaigns.

1 Introduction

Communication in High Frequency (HF) band is not considered to be reliable, due to large variations and highly dispersive characteristics of the HF channel: frequency selectivity due to multipath, Doppler spread, noise and interferences. Multicarrier modulation, specifically Orthogonal Frequency Division Multiplex (OFDM), is an appropriate approach for combating frequency-selectivity of the channel and narrowband interference. The idea is quite simple, yet very effective to avoid complex receivers and to provide more reliable communication. By sending a parallel set of narrowband signals, the channel can be approximated as frequency flat over each signal's bandwidth. This modulation leads to simple frequency-domain channel equalisation, consisting of one complex coefficient per subcarrier. Although frequency selective channels are well dealt with using OFDM, HF channel still remains hostile due to random signal attenuation affecting the whole band, and the presence of multiple sources of interferences due to human activity and atmospheric phenomena. The way to mitigate such impairment is to exploit diversity, which enables to transmit over desirably uncorrelated channels.

This paper describes parts of the work developed in the M3HF project (Multicarrier, Multiband, Multiantenna systems in HF communications, www.m3hf.eu), whose main goal is to propose practical solutions to increase reliability and capacity in HF communications. Theoretical and simulated studies are corroborated by real links for different diversity strategies: i) frequency bands to exploit the incoherence amongst them, ii) multicarrier exploiting two dimensional (time and frequency) coding and interleaving, and iii) antenna diversity through radiation pattern, and spatial and polarisation diversities. The results shown here focus on the last two strategies, multicarrier and antenna diversities; for the latter, we focus particularly on spatial and polarization diversities.

The main goal of the M3HF project is to make real and practical proposals to increase the reliability and capacity in HF communications according to the typical scenarios where these trans-horizon communications are used. From the two sides that any communication has, in a HF communication one of them is typically a fixed ground station and the other one is a mobile station, as it can be a vehicle, ship or airplane. Ground stations usually do not have operational restrictions, unlike mobile stations which are subject to stringent restrictions on power, space or antennas. These restrictions severely limit the possible diversity strategies that may be implemented at transmission. Even for ground stations, space-time or space-frequency diversity implementations using Alamouti codes [1,2] are extremely complex due to antennas coupling (transmission power can be several hundreds of Watts). Large separation between antennas avoids such a coupling, but introduces the critical issue of synchronization amongst transmitters. At present, we do not have a working implementation of multi-antenna transmission; the transmit diversities implemented in our system are: time, frequency, multicarrier and multiband. At reception, frequency and polarisation diversities seem to be the most suitable as space is a critical restriction. Moreover, polarisation diversity is the only strategy that keeps the same system parameters (power, bandwidth, throughput, etc.) as in single-input single-output (SISO) system, which is an important aspect if we are to compare performance of the new and legacy systems.

From long time ago the scientific community have experimented with diversity in HF communications. In [3] a comparison of space and polarisation diversity is made and it is concluded that both systems are equivalent. In [4] frequency and polarisation diversities are compared, and also concludes that polarisation diversity in particular can actually provide significantly better results than frequency diversity. In [5] polarisation studies were carried out using standard and non-standard modems and they conclude that the performances in the bit error rate and reliability of the link increase significantly. However, up to our knowledge, no studies in HF have been carried out using multicarrier transmissions and applying the combination strategies in the demodulation process into the modem. All the combinations of the previous studies were carried out on the antenna signal as aditive combination or signal selection.

2 System Description

Table 1 shows the most relevant parameters about the transmitting station and receiving stations. The HF stations are located in Gran Canaria (Canary Islands) and Madrid, Spain: a HF mid-latitude 1800km long link from south to north. The receiving station has two locations: Madrid city with a Yagi antenna (location A), which is the same antenna used at the transmitting station, and El Casar with two dual monopole vertical-horizontal polarised antennas (location B). Locations A and B are 40Km apart, and the distance between the two antennas at location B is 75 meters. Figure 1 shows the block diagram of the signal path in location B, where the received signal feeds four R&S EK895 receivers and the audio signal is sampled and fed to the HFDVL (HF Data+Voice Link) modem, which is described below. All receivers are configured similarly and no actions are taken on the received signal prior to being input into the modem. The transmitter site works with a 1Kw amplifier, but the RMS power measured at the amplifier's output is lower than 300w due to the multicarrier signal's high Peak to Average Power Ratio (PAPR).

	Transmitter side	Receiver side	
		Location A	Location B
Location	Gran Canaria (Canary Islands)	Madrid (City)	El Casar (Guadalajara)
Environ.	Semi-rural	Urban	Rural
Antenna	Yagi (4 elements)	Yagi (4 elements)	Two dual V-H polarized (active)
Radio	R&S XK2100L (Tx/Rx)	R&S XK2100L	Four R&S EK895
Amplifier	1Kw		
Distances	1800 Km		
		40 Km	
			75 meters

Table 1: Transmitting and receiving station descriptions

The HFDVL modem is basically a plain OFDM modem with the same structure for digital voice and data communications. The former is described in detail in [6] and uses a very efficient delay-sensitive MC-CDMA signalling (OFDM-CDM). The modem has the following characteristics: signal bandwidth is 2.7KHz with 73 carriers (60 for data and 13 interleaved pilots), subcarrier spacing is 37.5Hz, 4QAM constellation, 30 OFDM symbols per second, and cyclic prefix of more than 3 milliseconds. There are important enhancements in the data modem necessary to deal with the requirement of data transmissions. Indeed, voice requires a lower error rate (BER around 10^{-2} when using a MELP vocoder suffices). Also, data is typically not limited by severe delay constraints. Therefore, for data transmission we adopt a robust coding strategy: LDPC codes using LLR as soft bits with code rates of 1/2 or 4/5. Besides, in order to provide a wide range of performance results, higher size constellations were implemented (up to 64QAM). Figure 2 shows a block diagram with the main aspects of the modem. A detailed description and performance can be found in [7].

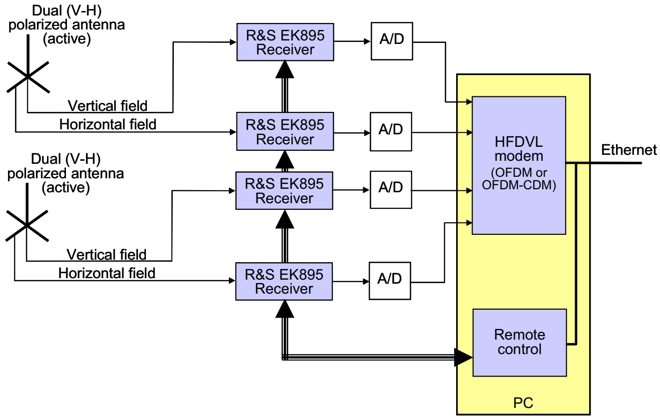
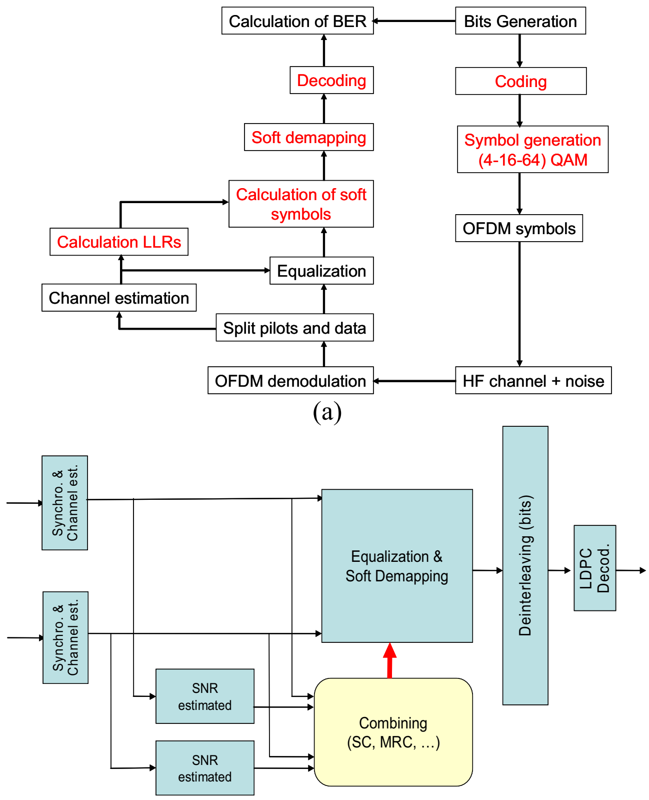


Figure 1: Block signal path in location B.



(b)

Figure 2: (a) SISO block diagram of data modem (black blocks are common with digital voice modem); (b) block diagram of reception side of HFDVL when multiple inputs are present.

When multiple inputs are present, all received signals are demodulated in parallel and then combined in order to recover the transmitted OFDM symbol. Although several combination techniques have been implemented, we will focus here on: OFDM symbol Selection Combining (SC-symbol) using as criterion the estimated SNR, carrier SC (SC-carrier) using as criterion the maximum of the channel gains of different carriers, and Maximum Ratio Combining (MRC) with and without weighing by the estimated SNR [8]. The HFDVL modem runs in real time on a Linux-based PC, with all the processes related to time and frequency synchronization acquisition and tracking, channel and SNR estimation (actually Signal to Noise+Inteference Ratio) done in parallel, as shown in Figure 2 (b).

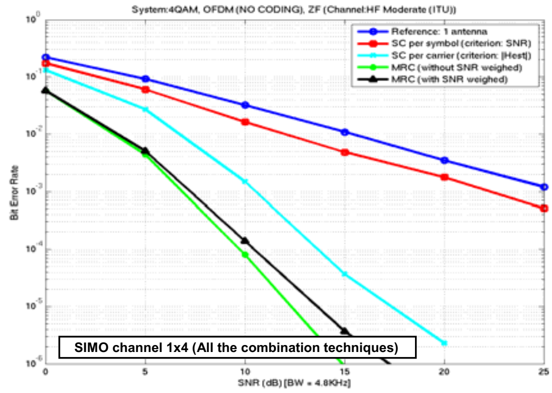
3 Simulated results

Performances of combination techniques implemented in the HFDVL modem were evaluated in a first step under simulation. In Figure 3 is shown the results for a 4QAM-OFDM, without coding, using Zero Forcing (ZF) as criterion to equalize the received signal, ITU-R moderate HF channel (2 rays, 1 msec of time spread and 0.5Hz of Doppler spread) and four reception antennas. In Figure 3 (a), where the different techniques are compared under uncorrelated channels, can be seen that the best technique is MRC with a gain over the SISO situation of one to two orders in the range of 0 to 10 dB of SNR in 4.8KHz of bandwidth. It is unusual to find SNR higher than 10dB on average in a real HF communication, so we must not expect more than two orders of gain in the real world. SC-symbol technique shows the worst performances, less than half order in all the SNR range. This happens because all the channels under simulation have the same statistical characteristics and for SC-symbol technique is similar to the case of computing the average of independent realizations of the channel in each symbol. However, when we introduce coding or the channels parameters are different between them, the gain of SC-symbol is very high, on one order or more (the results are not shown here by length restrictions). So we must expect a very good behaviour of the SC-symbol technique also in the real environment.

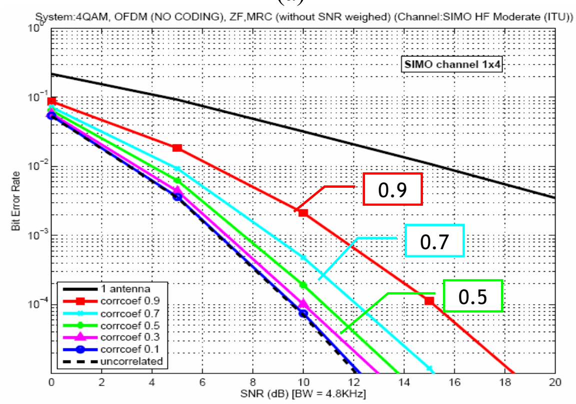
In Figure 3 (b) the MRC performance obtained for different degrees of correlation between moderate HF channels is shown. It is very important to remark than when we have a correlation of 0.7 the gain is significatly high and when it is 0.5 or less the performances are nearly the same as if we have been working with uncorrelated channels. In the case of two antennas (not shown here) with a correlation of 0.7 the perfornace is similar to the uncorrelated case.

4 Experimental results

In three different measurements campaigns, more than 6300 signals were registered and analysed during the first semester of year 2009 [9]. The first two were devoted to studies of spatial and polarization diversities. All the combinations were implemented using either OFDM or OFDM-CDM modulations with 4QAM constellation, LDPC1/2 coding or no coding, and block interleaver with lengths of 1.6, 3.3 and 5.0 sec or no interleaver at all.



(a)



(b)

Figure 3: HFDVL modem performances for different combination techniques on a moderate HF channel (a) uncorrelated channels; (b) MRC performance for different correlation factors.

For each of the aforementioned configurations, 40 signals of 1 min each were transmitted in the first campaign and 4 signals of 10 min each were transmitted in the second one. The third campaign was carried out with the same parameters as in the first one but also including band diversity, with a gap between bands of 36, 84, 132 and 324kHz. Due to space limitation, only a small set of the results of the first campaign will be shown here; the main conclusions are very similar for all the signals analysed, and they agree with previous studies carried out as described in the *Introduction* section (see [3-5]).

Table 2 shows the mean correlation measurement between the received signals in four different tests of 40 signals of 1 min each. The conclusions are the following: at location B, correlation between the antennas that are 75 meters apart and with the same polarisation is always less than 0.6, and the correlation between locations A and B (40Km apart) is less than 0.15. Correlation between different polarisations is in the range 0.3 to 0.4 when measured at the same antenna, and 0.25 to 0.3 when measured between antennas. All these results indicate that the correlation between antennas that are so far apart from each other and the correlation between polarisations at the same antenna are enough to obtain a high gain in system's performance.

Antennas	Test–1	Test–2	Test–3	Test–4
	Same polarization at different antennas (75m)			
V1-V2	0.61	0.45	0.50	0.55
H1-H2	0.42	0.30	0.38	0.34
	Different polarizations-same antenna			
H1-V1	0.35	0.39	0.42	0.23
H2-V2	0.40	0.36	0.31	0.30
	Different polarizations-different antenna (75m)			
H1-V2	0.37	0.28	0.28	0.35
H2-V1	0.36	0.28	0.26	0.35
	Different antennas with space diversity (40Km)			
H1-H3	0.06	0.11	0.08	0.11
H2-H3	0.07	0.10	0.09	0.11
V1-H3	0.09	0.14	0.09	0.14
V2-H3	0.11	0.15	0.11	0.15

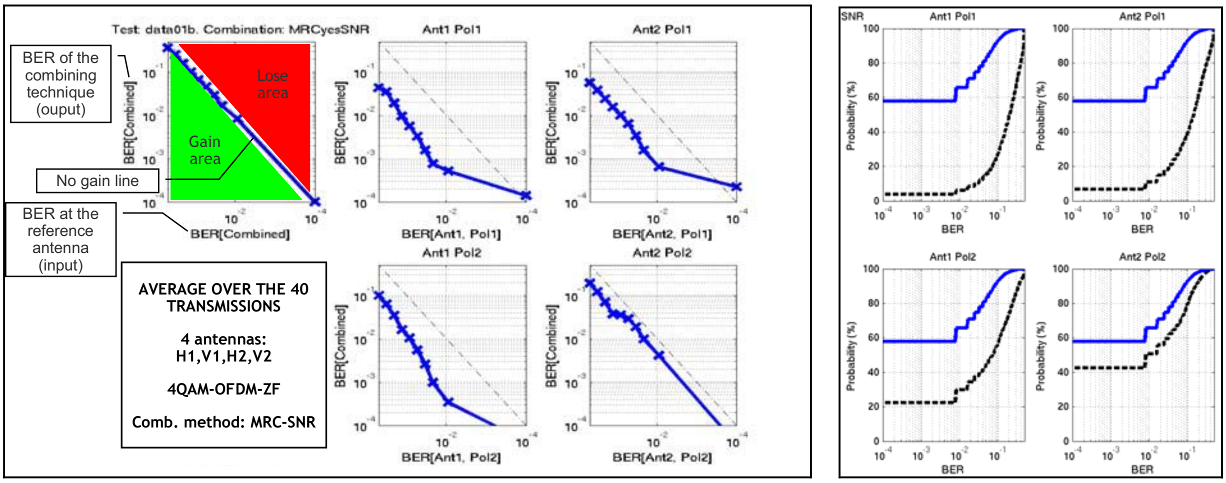
Table 2: Correlation between the received signals

Figure 4 (a) shows an example of a signal simultaneously received in the four antennas of El Casar and UPM. The transmitted signal from the station in Gran Canaria, a 4QAM-OFDM with ZF equalization in reception and using LDPC 1/2 without interleaving, is showed in the upper left corner of the figure. In the bottom left corner is showed the signal received in UPM and the other four photos correspond with the El Casar antennas. For the latter, in horizontal we have the same antenna with the two polarizations (V&H). It can be appreciated that errors are present in all the receptions, although as a demonstration of the diversity they do not follow the same distribution in each antenna. Even more, in this example more correlation is appreciated between same polarization in different antennas than different polarization in the same antenna. In Figure 4 (b) is shown the result of combining the four signals received in El Casar using different combination techniques. Of these the best performance is achieved by MRC technique, with and without weighted by SNR corresponding with signals in bottom right of the figure. After all the signals were analysed, we concluded that MRC weighted by the estimated SNR achieves the best performance in most of the cases, although SC-symbol provides also good results, and in some cases similar performance to MRC. It should be noticed that SC-symbol is the simplest to implement.

Figure 5 shows one of the most interesting results after a massive analysis of the signals, which in this case are, OFDM signals with no coding at transmission. Figure 3 (a) shows the diversity-induced gain in BER with respect to the performance obtained at the different no-diversity schemes at location B, where the combining is performed using the MRC technique weighted by estimated SNR. Abscissas represent the BER obtained for each SISO configuration, whereas ordinates represent the BER obtained after MRC combining. The results represent the average of the BER over the different received OFDM symbols. When points are below the diagonal, represented by the dashed line, a gain is obtained with respect to the SISO case, otherwise we have a loss. The figure shows the antenna configuration which is the predominant component in the combination process, marked as Ant2Pol2. For this antenna configuration, a gain of only half an order of magnitude was obtained. But for the other three configurations, a gain of one order of magnitude or higher was obtained. However, for unstable channels such as HF channels, there is another important parameter to consider, namely link reliability. Reliability must be understood as the percentage of time that it is possible to get a given BER. Figure 3 (b) shows reliability for the same configurations as for Figure 4 (a). Compared to the predominant antenna configuration, reliability of the diversity scheme is nearly 20% higher (from 40% of the time to 60%), but for the other antenna configurations, the increase is dramatically higher, up to a 55%. In other words, link reliability between 5% and 40%, obtained for the SISO case, increases to 60% after MRC combining. It is worth pointing

(a) (b)

Figure 4: An example of signal received in El Casar and UPM (a) SISO reception; (b) SIMOx4 reception, combining the four El Casar antennas with different combination techniques.



(a) (b)

Figure 5: Analysis for 4QAM-OFDM with no coding and MRC weighted by SNR (a) Average BER performances; (b) Average reliability performances.

out that the antennas are only 75 meters apart; furthermore, in a SISO system, no a priori knowledge about which antenna configuration will be the predominant component is possible. Regarding the increase in link reliability in the band diversity campaign, the best result was less than 50% (from 25% to 75%) when the gap between bands was 324kHz.

5. Conclusions

In practical HF communications, only a limited set of diversity strategies can be implemented. We have studied the performance of multicarrier transmissions with coding in time and frequency domains together with several combining techniques at the receiver end. Polarisation diversity has low implementation complexity in most cases, and yet provides very good performance when MRC is applied. The performance obtained with polarisation diversity with one antenna is similar to that obtained with spatial diversity resulting from two antennas 40km apart. BER gains of more than one order of magnitude are possible although the most interesting results are related to reliability of the communication link, which were shown to improve dramatically. Furthermore, SC-symbol technique, which is the simplest to implement, was shown to achieve performance similar to that of MRC in some scenarios.

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