MULTIPLE-INPUT ADAPTIVE COMBINER-EQUALIZER FOR WIRELESS COMMUNICATIONS

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Abstract: Receiver diversity is one of the most efficient techniques against fading and interference effects. MRC (Maximum Ratio Combining) was proven to ensure the highest diversity gain, but it is also the most complex compared to other combining techniques. In this paper we propose a multiple-input adaptive combiner-equalizer that provides better performance at lower complexity. The novelty of the solution lies in the unified combining-equalization approach - the two classical operations being performed simultaneously and not sequentially. A first set of simulations has shown that the performance of the proposed combiner-equalizer is superior to that of a classical MRC implementation.

Key words: *Adaptive Equalization, Receiver Diversity, MRC (Maximum Ratio Combining).*

I. INTRODUCTION

Receiver combining techniques are a means of implementing space diversity, and they involve the use of multiple antennas at the receiver. In receiver diversity, the independent fading paths associated with multiple receive antennas are combined to obtain a resultant signal that is then passed through a standard demodulator. Most combining techniques are linear: the output of the combiner is a weighted sum of the different fading paths or branches [1]. Some techniques also require signal co-phasing before summation (e.g. MRC).

The best combining performance (the highest combining gain) is given by the most complex technique - MRC (Maximum Ratio Combining). The complexity of MRC comes from the fact that the signals need to be co-phased before summing, and the SNR must be estimated for each branch. The result is obtained by adding the co-phased signals, which are also weighted with values proportional to their SNRs.

Our goal was to obtain a better combining performance, using a less complex mechanism. The approach is to add combining abilities to the equalizer, that is usually present on the receiver chain, and thus to transform it into a combiner-equalizer. This transformation is simple and it involves the addition of a tapped delay line for each branch. The equalizer will combine the delayed signals corresponding to each branch, and will try to generate an inverse channel model, based not just on one input but on all available branches (2, 3, …N). The equalizer becomes a MISO (Multiple Input Single Output) system.

This paper is organized as follows: the next section overviews the existing receiver diversity techniques and their established performance. Section three describes the proposed adaptive combiner-equalizer, which is a hybrid block based on adaptive linear neuron trained using the RLS algorithm. Section four presents our implementation in Matlab-Simulink and discusses the results. Section five compares our solution with other adaptive combining solutions and the last section contains our conclusions and future work.

II. RECEIVER DIVERSITY PERFORMANCE

There are several types of receiver diversity combiners, with different implementation complexity and overall performance: Threshold Combining (ThC), Selection Diversity Combining (SDC), Maximum Ratio Combining (MRC), and Equal Gain Combining (EGC). MRC outperforms the others on flat fading channels, and is not the optimum in dispersive fading conditions because of inter-symbol-interference (ISI). The challenge remains to adequate the spatial diversity solution to very specific scenarios.

In Threshold Combining (ThC) the received signals are scanned in a sequential order, and the first signal with a SNR level above a certain threshold is selected. This signal is used as long as its SNR is higher than the threshold value. When it falls below the threshold the selection process is reinitiated.

In Selection Diversity Combining (SDC), the SNRs of the received signals are continuously monitored so that the output of the combiner has a SNR equal to the maximum SNR of all the branches. SDC does not require co-phasing of multiple branches since only one branch output is used. To work properly, each antenna branch must have relatively independent channel fading characteristics. To achieve this, the antennas are either spatially separated, use different polarization, or a combination of both.

In Maximum Ratio Combining (MRC) the signals from the N receiver-branches are weighted with the complex conjugate of the corresponding sub-channel and then summed. Each signal is assigned a weight, w_i (fig. 1). This technique offers a means of combining the signals from all receiver branches, so that signals with a higher received power have a larger influence on the final output. This combining technique generally requires an individual receiver for each antenna element, and this is the main disadvantage compared to Selection Diversity. Also, since the signals are summed they must have the same phase to maximize performance. This requires not only separate receivers but also a co-phasing and summing device.

On the other hand, MRC produces an output SNR equal to the sum of the individual SNRs, which is an advantage because when none of the arriving signals have an acceptable SNR, this kind of combining may produce an output with an acceptable SNR. Another advantage of MRC is that, even if we have a Rayleigh channel for each branch; the combined signal has no longer Rayleigh distribution. More information about MRC performance may be found in [4] and [5].

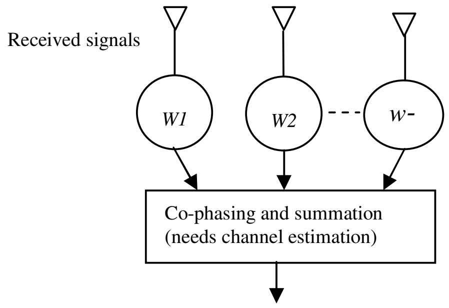

Figure 1. MRC combining principle

Regarding receiver combing, even if a performance hierarchy of these techniques is already established, we have analyzed the existing combining methods for different scenarios [11]. Our simulations, performed on an 802.11a WLAN Simulink platform, have confirmed that receiver combining techniques significantly improve performance in terms of packet error rate (PER), thus ensuring a higher link availability and reliability. Also the bit rate is increased depending on the propagation scenario. The main conclusion was that MRC outperforms the other combining techniques in terms of diversity gain, but this is only for flat fading channels, and it is not the optimum combiner in dispersive fading conditions because of inter-symbol-interference (ISI). The challenge remains to adequate the spatial diversity solution to very specific scenarios.

Diversity gains evaluated for different data rates are reported in [12], for eight antennas. Switch diversity is reported to provide a gain of up to 2 dB, corresponding to a 20% range improvement. For Selection Diversity, the gain lies between 7 and 9 dB, meaning 50% system range improvement. MRC provides an even higher diversity gain, 12-16 dB depending on the data rate chosen; the system range is improved with up to 100%.

The aspects that increase the MRC complexity are:

a) Co-phasing of the signals. Before summing the signals it is very important to make sure that the signals are in phase. The same principle is used by RAKE receivers. Usually, the solution is to use delay lines and an algorithm that estimates the delay for each branch, and this obviously increases complexity. Combining more than one branch signal requires co-phasing, where the phase θ_i of the i^{th} branch is removed through the multiplication by $w_i = a_i e^{-j\theta i}$ for some real-valued a_i. This phase removal requires coherent detection of each branch to determine its phase θ_i.

b) Computation of the weights. Equation (1) computes the gain of each branch and the weights are: $w_i = a_i e^{-j\theta i}$. This implies a method for estimating the SNR on each branch, and this in turn increases the complexity.

$$a_i = \frac{SNR_i}{\sum_{i=1}^{N_{Rx}} SNR_i} \quad (1)$$

where: a_i is the gain of branch *i;*
SNR_i is the instantaneous SNR of branch *i;*
N_{Rx} is the number of receiver antennas.

III. THE PROPOSED ADAPTIVE COMBINER-EQUALIZER

The proposed combiner-equalizer (fig. 2) is based on the following principles:

(1) tapped delay lines are a solution for correctly combining delayed signals without co-phasing, because they enable access to different delayed versions of the signals.

(2) the combiner-equalizer may be seen as a classifier and its primary goal is to classify the received symbols (according to the modulation scheme). The classification accuracy is more important than the inverse channel modelling accuracy.

(3) a general solution for classifying vectors is to use linear or non-linear neural networks. The simplest and fastest structure (widely used for adaptive equalizers) has one linear neuron and the weights are updated using algorithms such as LMS (Least Mean Squares) or RLS (Recursive Least Squares).

(4) each received signal (branch) adds information that should not be ignored because this information helps the neural network classify the inputs more accurately. At the same time, too much information leads to a slower network because of additional weight computation. All branches are a priori important, and it is up to the combiner-equalizer to combine them properly.

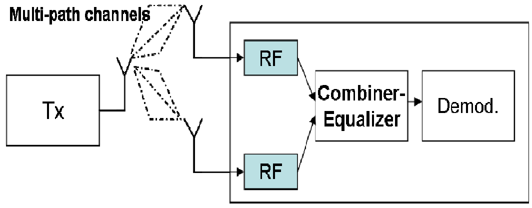

Figure 2. The place of the combiner-equalizer on the transmission chain

Figure 3 describes the structure of the proposed combiner-equalizer. This structure is obtained by adding tapped delay lines to a linear adaptive equalizer [6], one for each branch. We have chosen a linear equalizer because it is less complex than a non-linear one (i.e. Radial Basis Functions - RBF or fuzzy based equalizer). The same principle is applicable for non-linear equalizers also.

Additional tapped delay lines are necessary in order to have access to the previous samples of the available branches. The number of delay cells depends on the maximum delay spread supported by the system. The minimum number of cells must be higher than the maximum delay, divided by the sample time (considering the worst case scenario - outdoor conditions).

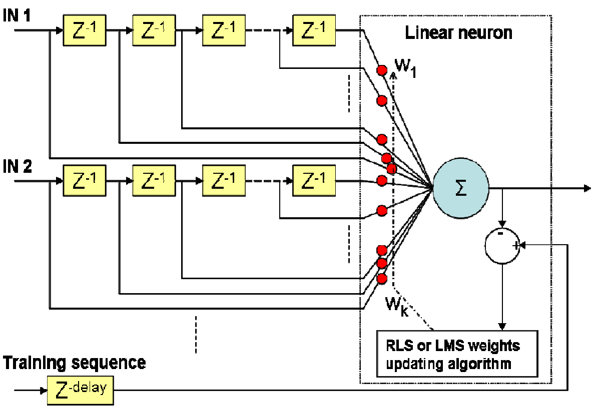

Figure 3. The proposed multiple-input adaptive combiner-equalizer

The delayed versions of the different arriving signals are the inputs of a linear neuron. The same algorithm used by the equalizer, LMS or RLS, will be applied for the additional inputs and will update all the weights. The adaptation algorithm uses the same training sequence that was used for the single-input, regular equalizer. From this point of view, the combiner-equalizer works exactly as a regular adaptive equalizer.

The proposed structure is equivalent to a set of FIR filters that are using the same summing unit and the same training algorithm. There is no need to co-phase the input signals of the combining-equalizer. There is no need to estimate the SNR for each branch. Instead, the combiner-equalizer minimizes the output error and estimates the weights corresponding to each delayed signal using the training algorithm. We consider that there is no need here to explain how the weights are adapted since the LMS and RLS algorithms are well known in the adaptive filtering.

The complexity of the proposed solution is measured in a number of additional delay cells necessary for the multiple inputs, and in the extra operations needed to update the additional weights. In our simulations, we have used 12 delay cells for each branch for a good performance in simulated outdoor conditions. For indoor conditions the number of delay cells may be reduced to 4 to 6 cells per branch. The LMS algorithm is faster than RLS but the performances are sensibly higher for RLS. The complexity may be reduced by decreasing the number of delay cells per branch, and by using the LMS algorithm.

IV. SIMULATION AND ANALYSIS

We have implemented the proposed adaptive combiner-equalizer in Simulink, starting from the 4-QAM (QPSK) adaptive equalization block available with Matlab-Simulink (fig. 5). The modified block now manages two or three inputs. We have also replaced the Rician channel block with a selective fading channel, having a Rayleigh distribution.

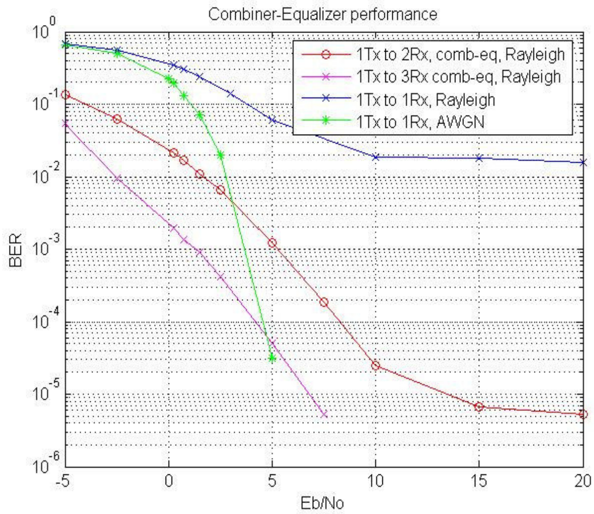

Figure 4. Adaptive combiner-equalizer performance simulation on Rayleigh channels (QPSK transmission)

Our simulations were based on three test scenarios: the 1Tx-1Rx configuration, with a regular equalizer (no combining), the 1Tx-2Rx and 1Tx-3Rx configurations with the adaptive combiner-equalizer. The channel blocks were Rayleigh-based, with Doppler shift values ranging from 20 to 50 Hz, and delays from 1µs to 6 µs (multipath outdoor environment – worst case scenario).

From the first set of simulations we can conclude that the combiner-equalizer performance is very good (as depicted in figure 4). For a SNR = 0.5dB, 1Tx-1Rx configuration (regular equalizer), we obtain a BER = 0.3444. The combiner-equalizer BER = 0.0216 for two branches and BER = 0.00137 for three branches (all branches having the same SNR = 0.5dB). The combining gain is 20dB (for M = 2) at a BER = 0.02 and higher for lower BER values.

Figure 4 shows the test results for an E_b/N_o ranging from -5 to 20 (SNR between -10 and 40 dB). For instance, the 1Tx-2Rx performance for a SNR = 0dB, BER = 0.02, is comparable to that of the 1Tx-1Rx for a SNR = 20 dB. The same BER value may be obtained using three branches for a SNR = -6.5 dB.

During these tests, we have observed some other secondary aspects such as:

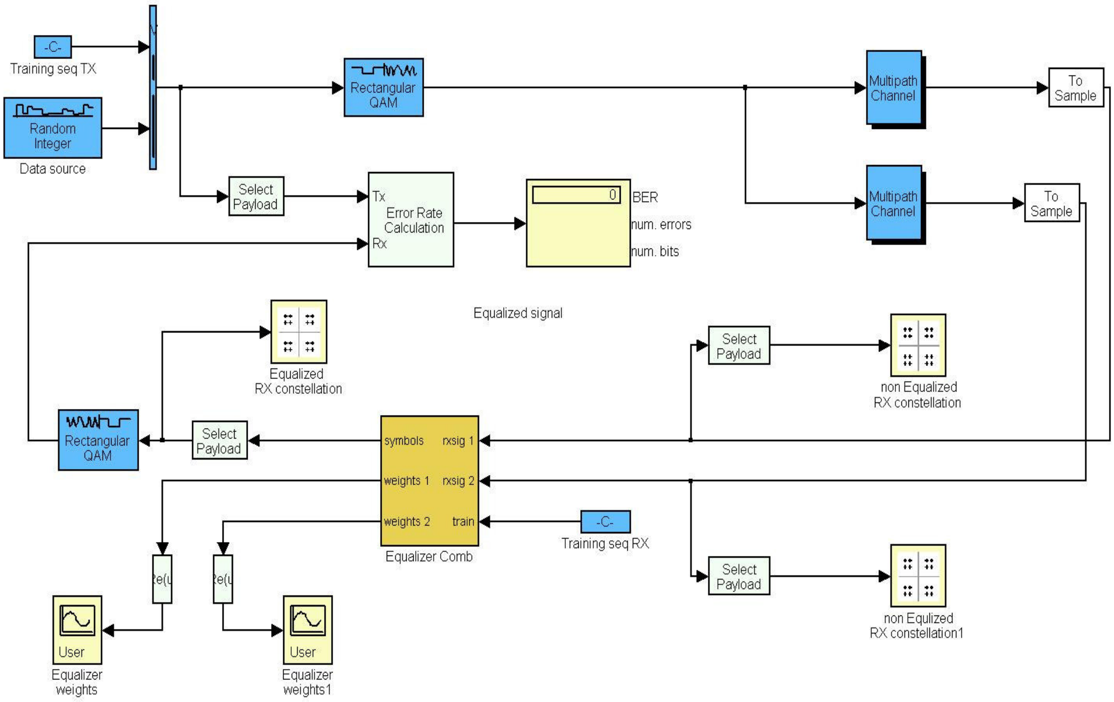

Figure 5. Integration of the multiple-input adaptive combiner-equalizer onto a QPSK transmission chain

(1) The 1Tx-1Rx configuration, with a regular equalizer, is not very sensitive to the number of delay cells (8 are usually enough) but the combiner-equalizer performance is better when we use about 10 to 12 delay cells on each branch; and this is for outdoor conditions.
(2) the RLS-based weights updating performs better than LMS, but it needs more computational resources; the tests presented here are based on RLS.

In order to make our results easier to reproduce elsewhere, we present the simulation parameters. The results were obtained using a modified version of the Simulink QPSK adaptive linear equalization block diagram (with Embedded Matlab). The combiner-equalizer was obtained by modifying a LMS/RLS equalizer, and eliminating the pre-equalization block used in the initial block diagram. We have used a 50-symbol training sequence per each 200-payload-symbol frame (as in the initial implementation).

The 1Tx-1Rx configuration was tested for dispersive fading, with: sample time 1e-6, gain vector [0 -3], delay vector [0 1e-6] and Doppler shift 50 Hz. For the 1Tx-2Rx test an additional channel was used with the parameters: gain vector [0 -3 -5], delay vector [0 1e-6 5e-6] and 30 Hz Doppler shift. For the 1Tx-3Rx scenario we have used another additional dispersive channel with the parameters: gain vector [0 -3 -3 -4], delay vector [0 1e-6 5e-6 8e-6] and 20 Hz Doppler shift. For the two-input combiner-equalizer, we have used the same parameters for the RLS algorithm but it was necessary to reduce the LMS learning step to 0.01 instead of 0.025. For the three-input combiner-equalizer, we have used a 0.005 learning step for the LMS, and we have changed also the RLS parameters, 0.995 for lambda and 0.025 + 0i for delta.

About 1Mb of data was transmitted for each simulation. Because of this reduced number of transmitted bits, we expect a satisfying precision in the -5 to 10dB E_b/N_o range, and a lower precision between 10 and 20 dB.

V. RELATED WORK

We discuss here some MRC optimizations and combining-equalizing attempts that can be found in recent and old literature. An optimization idea for MRC, and also for MIMO systems, is to reduce the number of active branches, in order to reduce the system complexity. Only the “good” (high-SNR) branches will be selected [7]. This solution does not increase the performance significantly and we still need to estimate the signal quality (SNR) for each branch. By deliberately cancelling part of the information that arrives at the receiver, we affect the link availability.

In [9], the authors propose a generalized selection combining scheme based on a threshold. In this proposal, only the branches with signal levels above a specified threshold are combined. A threshold-based generalized selection combining (T-GSC) scheme is proposed. This proposal reduces the complexity but does not increase the performance in terms of BER, the disadvantage of deliberate signal cancellation being still present.

Some adaptive solutions try to jointly use different techniques, for instance adaptive modulation and diversity combining [8]. Our solution may be also combined with other techniques (if necessary) and this is still to be tested.

The closest approach to our proposal is that of Balaban and Salz [13], [14] who demonstrate the performance advantage of joint combining and equalization, which is also used in a combiner-equalizer Alcatel patent [15] from '97. In both cases there are two distinct functions: first combine, then equalize or first equalize on each branch and then combine. In the patent case there are no numerical results available, but some of the Balaban & Salz versions of the dual diversity combiner-equalizer perform better then our implementation, some do not.

VI. CONCLUSIONS AND FUTURE WORK

In this paper we propose an adaptive receiver combining method based on a unified combining and equalization principle. The novelty of our solution lies in the unified combining-equalization approach - the two classical operations being performed simultaneously and not sequentially as in the examples presented in the 'related work' section. The advantages of the proposed solution are: easy to extend for N receiver antennas, easy to integrate in a transmission chain, low complexity (compared to similar solutions), increased diversity gain (compared to classical MRC implementations).

The combiner-equalizer may be easily obtained by adding delay taps to a single-input adaptive equalizer, one for each branch, thus obtaining a multiple-input equalizer. The complexity of the proposed solution is measured in the number of delay cells and extra computation necessary for the additional weights that appear due to this extension. But, compared to the regular MRC, there is no need of co-phasing and gain computation for each branch (eq. 1). The combiner-equalizer principle is simple: to classify each symbol, function of previous symbols on each branch, using the training sequence for error estimation.

The proposed solution enables us to adjust the complexity-performance balance, by modifying the number of delay cells per branch, and by choosing the LMS algorithm instead of RLS. The performance can probably be increased even more by using a non-linear neural network like RBF.

Although we have performed relatively short tests, we think they are relevant enough for estimating the performance of the adaptive combiner-equalizer. As future work, we intend to integrate and test the combiner-equalizer onto a multi-carrier transmission chain. Another idea for the future is to add the code correction function to the proposed combiner-equalizer [10], in order to see if the combined solution outperforms the regular solution. An analytical final analysis is necessary - for the moment the results are based on simulations. Other MRC-based implementations also need to be simulated in the very same conditions for more accurate comparison.

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