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To cite this version:

Thierry Dubois, Maryline Hélard, Matthieu Crussière. Time Reversal in a MISO OFDM system: Guard Interval design, dimensioning and synchronisation aspects. WWRF29, Oct 2012, Berlin, Germany. <hal-00783205>

HAL Id: hal-00783205

https://hal.archives-ouvertes.fr/hal-00783205

Submitted on 31 Jan 2013

Time Reversal in a MISO OFDM system: Guard Interval design, dimensioning and synchronisation aspects.

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***Abstract*— This article presents the way to combine TR and OFDM, either in the time domain or in the frequency domain by adding a filter at the transmitter side. The equivalent channel being the autocorrelation of the impulse response of the channel, the channel coefficient affecting each subcarrier is thus purely real, allowing a simple receiver as well as a simple transmitter. Moreover, the shape of the channel and its double length must be taken into account when designing the guard interval, in order to keep the circularity of the channel matrix at the receiver side. Finally, some simulation results show that the guard interval may not be twice as long as the initial channel, allowing to take advantage from all the benefits of time reversal while keeping the same spectral efficiency as a classical OFDM system.**

***Index Terms*— Guard Interval, OFDM, MISO systems, Time Reversal**

I. INTRODUCTION

Nowadays, most of communication standards operates multi-antenna systems (WiFi, LTE…). These systems thus necessitate a multi-antenna pre-coding technique. However, the techniques used in these systems come with high complexity when the number of antenna increases.

A technique arises then as a simple technique to discriminate users and to design multi-antenna systems: Time Reversal.

Firstly experimented in acoustics and ultrasound domains [1][2][3], Time Reversal (TR) has also received attention recently for wireless communications [4][5][6]. Owing to its inherent time and spatial focusing properties, TR is now studied as a solution for future green wireless communications [7]. Its time focusing property allows having low inter symbol interferences at the receiver side. The spatial focusing allows discriminating user by only focusing the wave on the aimed user.

In fact, Time Reversal was highlighted to be suitable for MISO systems as it is a simple pre-filtering technique for any number of transmit antennas and leads to low complexity receivers [8]. Moreover, it reduces the delay spread of the channel [9]. However, to achieve good performance in terms of delay spread reduction and spatial focusing, Time Reversal must be realized either over a large frequency bandwidth or with multiple antennas, or using rate back off [10][11].

On the other hand, OFDM was chosen as the modulation in most communication standards (WiFi, LTE, WiMAX...) owing to its good performance in multipath environment. In fact, OFDM allows making rid of the frequency selectivity of the channel by sending constellation symbols on sub-bandwidths smaller than the coherence bandwidth of the channel, experiencing thus flat fading channels. This technique allows designing a simple receiver that only consists of a one-tap equalizer per subcarrier. This comes however with a loss of spectral efficiency, as a guard interval needs to be introduced between the OFDM symbols to avoid Inter Symbol Interference.

Hence, the combination of OFDM and TR seems encouraging since TR is realized over the bandwidth of the entire signal, while the data are sent over rather small bandwidths. In case TR is implemented in a system, the equivalent channel of the system has a particular form, which has to be accounted for in the design of the system.

In this paper we show how TR and OFDM can be combined in order to efficiently take advantage of both TR properties (time and spatial focusing gains) and OFDM benefits (multi-path mitigation, receiver simplicity). We detail the OFDM transmitter and receiver including the guard interval dimensioning and the synchronisation function.

The rest of the article is organized as follows. In section 2, the way to combine OFDM and TR either in the time domain or in the frequency domain is presented in a MISO context and the two implementations are compared. In section 3, two ways of designing the guard interval and the matching synchronizing technique are presented. In section 4, an advantageous way of synchronizing the FFT window at the receiver side is presented. In section 5, some results on the guard interval design and dimensioning are shown. The conclusions and perspectives are drawn in the final part.

II. OFDM AND TIME REVERSAL

Time Reversal principle is presented in details for acoustic waves in and for electromagnetic waves in. For wireless communications, and as illustrated in Fig. **1**, TR consists in pre-coding the signal to be transmitted with the time reversed and conjugated version of the Channel Impulse Response (CIR) between the transmit and the receive antenna. In this figure, c_k is a complex constellation symbol, $\boldsymbol{g_e}$ is the transmit shape filter, $h(t)$ is the complex baseband equivalent of the CIR and $\boldsymbol{h}^{\dagger}$ is the TR filter corresponding to the discrete version of the time reversed and conjugated CIR $h(t)$. TR requires thus the knowledge of the CIR at the transmitter side, which makes it suitable for a closed loop system.

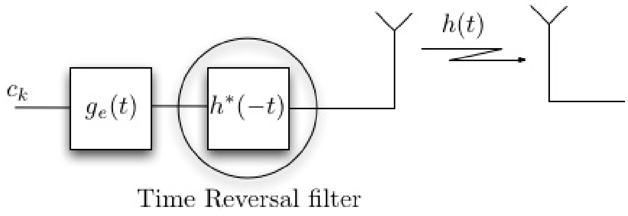

Fig. 1. Communication system using Time Reversal

The global transmission can be seen as a transmission with an equivalent channel being the autocorrelation of the CIR: $g(t) = h(t) \otimes h^*(-t)$, where $\otimes$ denotes the convolution product. In the time domain, $g(t)$ consists of a central peak of high amplitude and some side lobes. When the symbol duration is larger than the equivalent channel time dispersion, the receiver can merely consist of a threshold detector. Obviously, as in any transmission involving a multi-path channel, OFDM allows getting rid of the remaining Inter Symbol Interference (ISI) by increasing the symbol duration.

In this section, the way to operate TR with an OFDM system either in the time domain or in the frequency domain is presented as well as the advantages of such a combination. The implementation of TR in the time domain is developed in part II.A, which will later be called Time Domain TR-OFDM, and in the frequency domain in part II.B, which will be later called Frequency Domain TR-OFDM.

A. *Time Domain TR-OFDM*

As illustrated in Fig. 2, applying TR in the time domain for an OFDM system consists in filtering the signal after the Guard Interval (GI) insertion. In this diagram, the elements of the digital filter $\boldsymbol{h}^{\dagger}$are the discrete samples of $h^*(-t)$ according to the sampling frequency of the system, i.e. $\boldsymbol{h}^{\dagger} = \{h^*_{L-1}, \cdots, h^*_1, h^*_0\}$, with L the length of the discrete CIR. Due to the linear convolution operation, OFDM symbols will experience an equivalent channel $\boldsymbol{g} = \boldsymbol{h}^{\dagger} \otimes \boldsymbol{h}$ twice as long as the initial channel length L.

Hence, the GI duration shall be larger than $2L-1$. $C_{m,n}$ represents the complex constellation symbol to be transmitted on the m-th subcarrier during the n-th OFDM symbol. S/P and P/S stand respectively for Serial to Parallel and Parallel to Serial conversions. IFFT represents the Inverse Fast Fourier Transform.

Let $\boldsymbol{H} = \{H_{m,n}\}$ ($\boldsymbol{H}^{\dagger} = \{H^*_{m,n}\}$ respectively) be the vector of size N_{FFT} representing the frequency domain version of the channel obtained by performing a N_{FFT}-point Fast Fourier Transform on discrete CIR $\boldsymbol{h}$ ($\boldsymbol{h}^{\dagger}$ respectively). Element $H_{m,n}$ is thus the channel fading coefficient on the m-th subcarrier of the n-th OFDM symbol.

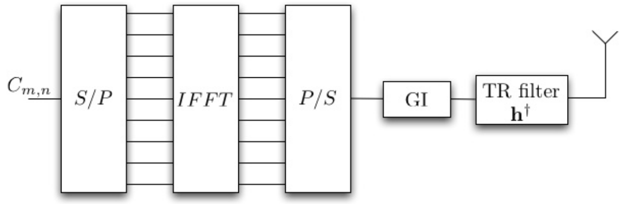

Fig. 2. OFDM transmitter including a Time Reversal filter

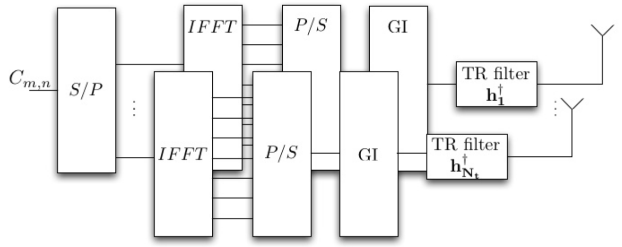

Fig. 3. MISO OFDM system including Time Reversal

Assuming a perfect synchronization and a $2L-1$ dimensioned GI, the circularity property of the FFT leads to a point-wise multiplication in the frequency domain. Thus, the complex symbol received on the m-th subcarrier of the n-th OFDM symbol will have the expression:

$$\begin{aligned} R_{m,n} &= H^*_{m,n} H_{m,n} C_{m,n} + N_{m,n} \\ &= \left|H_{m,n}\right|^2 C_{m,n} + N_{m,n} \end{aligned} \qquad (1)$$

where $N_{m,n}$ is the additive white Gaussian noise term associated to m-th subcarrier of the n-th OFDM symbol.

The channel factor $\left|H_{m,n}\right|^2$ is due to the equivalent channel being the autocorrelation of the CIR. It can be highlighted that, assuming a perfect synchronization, the equivalent channel coefficient affecting each subcarrier is purely real. This allows realizing a very simple MISO transmission by filtering on each antenna by the time reversed CIR between the transmit and the receive antennas, as depicted in Fig. 3. In this diagram, $\boldsymbol{h}_{\boldsymbol{k}}^{\dagger}$ is the time reversed CIR between the k-th transmit antenna and the receive antenna.

The expression of the received signal after the FFT operation is thus:

$$R_{m,n} = \sum_{k=1}^{N_t} \left|H_{m,n,k}\right|^2 C_{m,n} + N_{m,n} \qquad (2)$$

The equivalent channel is still real and the contribution of each transmit antenna adds constructively at the receiver side.

B. *Frequency domain TR-OFDM*

It is also possible to apply the TR operation in the frequency domain, as depicted in Fig. 4. This operation is realized by precoding the symbols on each subcarrier by the conjugated channel coefficients obtained from the frequency version of the CIR obtained after a Fourier transform. Therefore, the transmitted symbols become $C'_{m,n} = H^*_{m,n} C_{m,n}$. Owing to the IFFT operation, the precoding carried out in the frequency domain translates into a circular convolution in the time domain. OFDM symbols will thus experience an equivalent channel as long as the initial channel length L.

Hence, the GI shall be longer than L only, instead of $2L-1$ in Time Domain TR-OFDM.

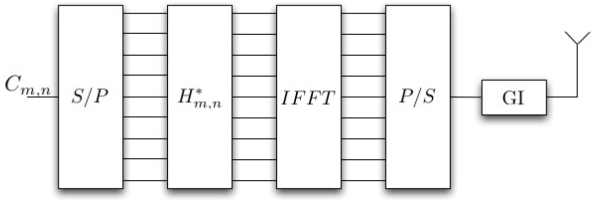

Fig. 4. OFDM transmitter using TR in the frequency domain

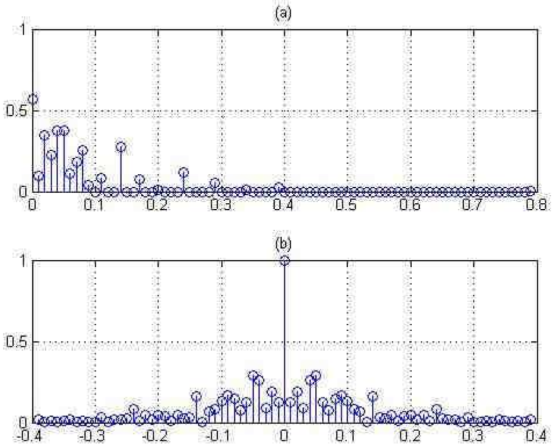

Fig. 5. Modulus of a BranA channel realization (a) and its autocorrelation (b)

Assuming a perfect synchronization and a L dimensioned GI, the received symbol after the GI removal and after the IFFT operation is thus:

$$\begin{aligned} R_{m,n} &= H_{m,n}C'_{m,n} + N_{m,n} \\ &= H_{m,n}H^*_{m,n}C_{m,n} + N_{m,n} \\ &= \left|H_{m,n}\right|^2 C_{m,n} + N_{m,n} \end{aligned} \tag{3}$$

It can be noted that the expression of the received symbol after OFDM demodulation is the same as in II.A. Consequently, and as illustrated in Fig. 5, the equivalent CIR keeps the same time focusing property. Moreover, a MISO system using TR in the frequency domain can be realized as shown in Fig. 6.

III. DESIGN OF THE GI

In case TR is implemented and as described in section II, the equivalent channel of the transmission is the autocorrelation of the channel. Hence, the channel is twice as long as the initial channel and its modulus is formed by a central peak and side lobes. For example, a realization of the BranA channel [12] is given in Fig. 5.

The modulus of the channel being different when combining TR to an OFDM system, the design of the GI must be modified. Indeed, the first observation is that the channel is theoretically twice as long as the original channel. The second observation is that the main tap of the channel to be considered is no longer one of the first taps, but the central tap.

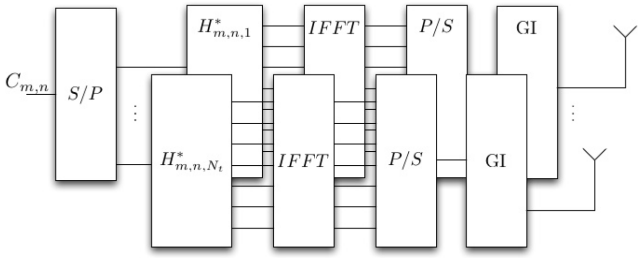

Fig. 6. MISO-OFDM system using TR in the frequency domain

A. *Classical Cyclic Prefix OFDM*

In a classical Cyclic Prefix (CP) OFDM system, the receiver synchronizes on the first tap of the channel as depicted in Fig. 7. With such an operation, it assures that the channel matrix is circulant. Indeed, the Cyclic Prefix GI consists in copying the last samples of the OFDM symbol in the GI. Considering the GI is of size L, the exact size of the channel, the emitted OFDM symbol $\boldsymbol{x}'$ of size $N_{FFT}+L$ has thus the expression:

$$\boldsymbol{x}' = \left[\underbrace{x_{N_{FFT}-L+2},\cdots,x_{N_{FFT}-1}}_{Cyclic\ Prefix},\underbrace{x_0,x_1,\cdots,x_{N_{FFT}-1}}_{\substack{Useful\ part\ of\ the\\ OFDM\ symbol}}\right] \tag{4}$$

where the samples x_k, $k \in \{0,1,\cdots N_{FFT}-1\}$ are the output of the IFFT operation. At the receiver side, the received symbol $\boldsymbol{y}$ becomes:

$$\boldsymbol{y} = \underline{\boldsymbol{h}}\boldsymbol{x}' \tag{5}$$

with $\underline{\boldsymbol{h}}$ being the $N_{FFT}+L \times N_{FFT}+L$ channel matrix equals to:

$$\underline{\boldsymbol{h}} = \begin{bmatrix} h_0 & 0 & \cdots & & & & 0 \\ h_1 & h_0 & 0 & \cdots & & & 0 \\ \vdots & & & & & & \vdots \\ 0 & \cdots & 0 & h_{L-1} & \cdots & & h_1 \\ 0 & \cdots & & 0 & h_{L-1} & \cdots & h_1 & h_0 \end{bmatrix} \tag{6}$$

This equation can be rewritten using only the useful part of the transmitted OFDM symbol $\boldsymbol{x} = [x_0, x_1, \cdots, x_{N_{FFT}-1}]$:

$$\boldsymbol{y} = \underline{\boldsymbol{h}}_{\boldsymbol{eq}}\boldsymbol{x} \tag{7}$$

where $\underline{\boldsymbol{h}}_{\boldsymbol{eq}}$ is the $N_{FFT} \times N_{FFT}$ matrix equal to:

$$\underline{\boldsymbol{h}}_{\boldsymbol{eq}} = \begin{bmatrix} h_0 & 0 & \cdots & & 0 & h_{L-1} & \cdots & h_2 & h_1 \\ h_1 & h_0 & 0 & \cdots & & 0 & h_{L-1} & \cdots & h_1 \\ \vdots & & & & & & & & \vdots \\ 0 & \cdots & & 0 & h_{L-1} & \cdots & & & h_1 \\ 0 & \cdots & & & 0 & h_{L-1} & \cdots & h_1 & h_0 \end{bmatrix} \tag{8}$$

Hence, the equivalent channel matrix is circulant and the FFT operation will lead to a point-wise multiplication in the frequency domain, allowing a one-tap equalization.

When implementing TR in an OFDM system, two strategies are possible: a double CP or a CP and a Cyclic Suffix (CS) as proposed in [6]. The equivalent channel of the transmission will be noted $\boldsymbol{g} = [g_{-L+1}, \cdots, g_0, \cdots g_{L-1}]$ with g_0 representing the central peak. Moreover, $\boldsymbol{g}$ being the autocorrelation of $\boldsymbol{h}$, the channel is anti symmetric and the following relation links the taps of the channel: $g_{-k} = g_k^*$.

The channel can thus be rewritten as $\boldsymbol{g} = [g_{L-1}^*, \cdots, g_0, \cdots g_{L-1}]$.

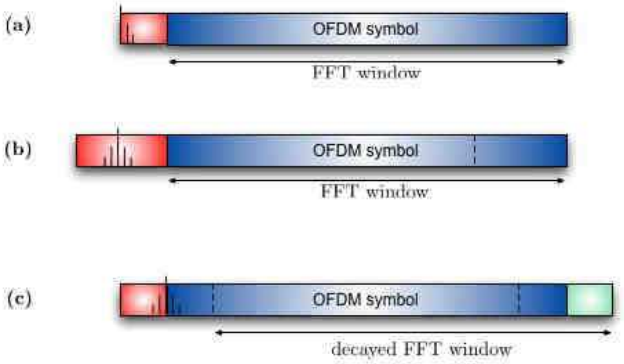

Fig. 7. Guard interval design and associated synchronization for classical CP-OFDM (a), TR-OFDM with a double CP (b) and TR-OFDM with CP and CS (c)

B. *Double Cyclic Prefix for TR-OFDM*

When doubling the CP, if the receiver synchronizes on the main tap of the channel, the channel matrix is no longer circulant, and ISI appears. In that case, the equivalent channel matrix is equal to:

$$\underline{\boldsymbol{g}}_{\boldsymbol{eq}} = \begin{bmatrix} g_0 & \cdots & g_{L-1}^* & 0 & \cdots & 0 & g_{L-1} & \cdots & g_2 & g_1 \\ g_1 & g_0 & \cdots & g_{L-1}^* & 0 & \cdots & 0 & g_{L-1} & \cdots & g_2 \\ \vdots & & & & & & & & & \vdots \\ 0 & & & & 0 & g_{L-1} & \cdots & g_1 & g_0 & g_1^* \\ 0 & & & & & 0 & g_{L-1} & \cdots & g_1 & g_0 \end{bmatrix} \tag{9}$$

Hence, the receiver must decay the FFT window by half the size of the CP, to place the main tap of the channel at the center of the CP as depicted in Fig. 7. The channel matrix becomes then circulant, and ISI is avoided:

$$\underline{\boldsymbol{g}}_{\boldsymbol{eq}} = \begin{bmatrix} g_{L-1}^* & 0 & \cdots & & 0 & g_{L-1} & \cdots & g_{L-3}^* & g_{L-2}^* \\ g_{L-2}^* & g_{L-1}^* & 0 & \cdots & & 0 & g_{L-1} & \cdots & g_{L-3}^* \\ \vdots & & & & & & & & \vdots \\ 0 & \cdots & & & g_{L-1} & \cdots & & g_{L-1}^* & 0 \\ 0 & \cdots & & & 0 & g_{L-1} & \cdots & & g_{L-1}^* \end{bmatrix} \tag{10}$$

However, with such an operation, the receiver introduces a time delay on the channel, since the main tap is placed in the middle of the CP and not at the beginning. Hence, a phase rotation appears in the frequency domain that needs to be compensated by the receiver. This phase rotation depends on the value of the time delay τ, which is half the size of the CP, and on the index of the subcarrier:

$$\begin{aligned} \varphi &= 2\pi\tau f \\ &= 2\pi\tau \frac{m}{N_{FFT}} \end{aligned} \tag{11}$$

where f is the frequency and m is the index of the subcarrier.

The receiver must then apply a phase correction factor to compensate for the time decay.

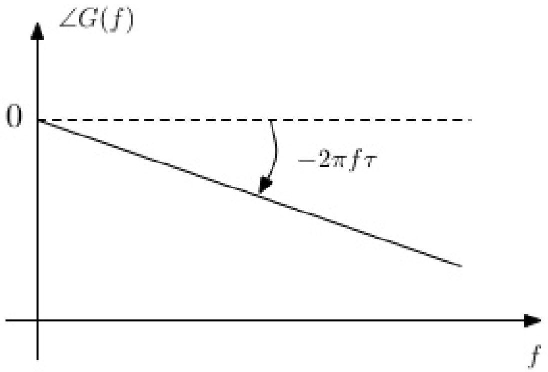

Fig. 8. Illustration of the phase rotation induced by a synchronization error

C. *Cyclic Prefix and Cyclic Suffix for TR-OFDM*

The second strategy, firstly proposed in [6], to design the GI is to have a CP of the same length as for a classical OFDM system, and to introduce a Cyclic Suffix (CS), which is the copy of the first samples of the OFDM symbol. Hence, the transmitted symbol $\boldsymbol{x'}$ becomes:

$$\boldsymbol{x'} = \Bigg[\underbrace{x_{N_{FFT}-L+2}, \cdots, x_{N_{FFT}-1}}_{Cyclic\ Prefix}, \underbrace{x_0, x_1, \cdots, x_{N_{FFT}-1}}_{\substack{Useful\ part\ of\ the \\ OFDM\ symbol}}, \underbrace{x_0, \cdots,}_{Cyclic\ Su} \tag{12}$$

The receiver in that case must synchronize as in the classical CP-OFDM case, i.e. on the strongest tap. However, the FFT operation is now realized after suppressing the CP and the L first taps of the useful part of the OFDM symbol. The equivalent channel matrix is the same as in the previous case and the circularity is thus kept.

Moreover, the FFT window is delayed with a time $-\tau$ which is the opposite of the decay on the channel. Consequently, the phase rotation compensates with the one coming from the delayed channel. Hence, in that case, no phase rotation has to be applied on the receiver.

IV. SYMBOL SYNCHRONIZATION

One of the main advantages of the combination of TR and OFDM is that the equivalent channel is real at the receiver side. This allows having a simple receiver and designing a simple MISO OFDM system. Another advantage of the real channel is the symbol synchronization. Indeed, if the receiver is not well synchronized, a phase term appears in the frequency domain, which is proportional to the time decay and to the frequency as illustrated in Fig. 8.

In this diagram, $G(f)$ is the Fourier transform of the equivalent channel of the system, τ is the synchronization error at the receiver and f is the frequency. Hence, from the reception of known pilot symbols distributed over the subcarriers of the OFDM symbols, the phase of the channel can be deduced on each of the subcarriers containing a pilot symbol. Then, by interpolating the slope of the phase as a function of the frequency, it is possible to retrieve the synchronization error. The receiver can then correct the synchronization from this information.

In a classical OFDM system, without TR, since the phase of the channel is not correlated from a subcarrier to another, this operation is not possible.

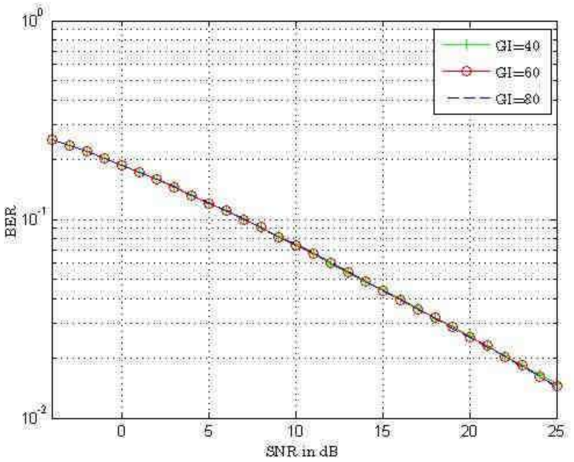

Fig. 9. BER as a function of the SNR for TR-OFDM in the time domain

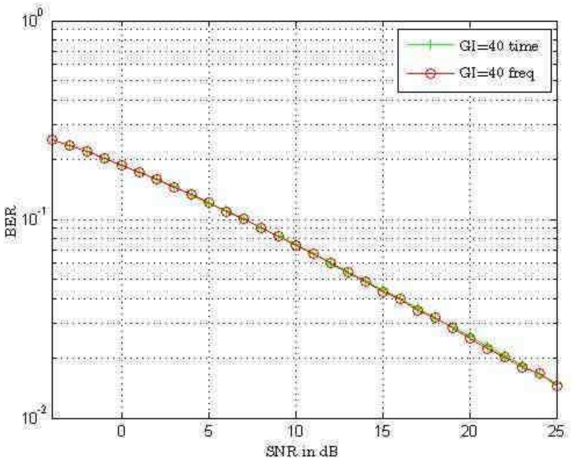

Fig. 10. BER as a function of the SNR for TR-OFDM in the time domain and in the frequency domain

V. DIMENSIONING OF THE GI

As described in section III, the equivalent channel of the transmission is theoretically twice as long as the channel $h(t)$. That is why the GI is considered to be twice as long in the same section. However, as reminded in section I, TR allows reducing the delay spread of the channel [9]. Hence, we demonstrate by simulations that it is possible to reduce the length of the GI in the system to the length of the GI in the classical system, allowing having the same spectral efficiency.

Some Monte Carlo simulations of a SISO TR-OFDM system are realized over a BranA channel [12] with several GI lengths, without taking into account the spectral efficiency of the system in order to compare the performance of each system . The implemented systems are the TR-OFDM system in the time domain, and the TR-OFDM system in the frequency domain. For the time domain TR-OFDM, the performance is identical if the GI is a double length CP or a CP+CS. The simulations are drawn for QPSK symbols, with a simple threshold detector. The performance of each solution is obtained by evaluating the Bit Error Rate (BER) as a function of the ratio of the transmitted power on the additive white Gaussian noise power. The results thus do not take into account the spectral efficiency of the system in order to compare the performance of each system.

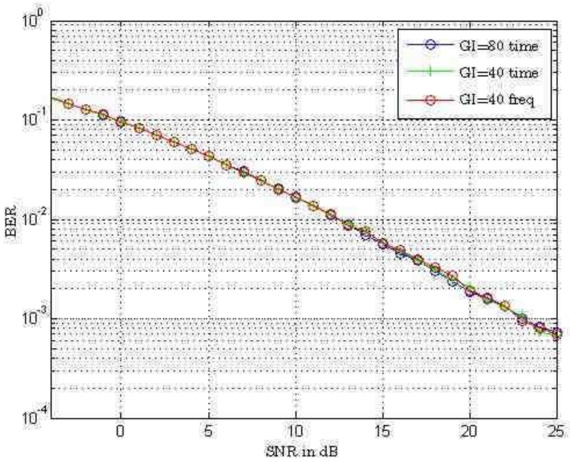

Fig. 11. BER as a function of the SNR for TR-OFDM in the time domain and in the frequency domain for 2 transmit antennas

For a SISO system, the performance of the TR-OFDM system in the time domain is shown on Fig. **9**. The reference performance is the result with the length of the GI equal to 80, which is equal to $2L$ in that case. One can observe that the performance remains equal to the optimal when the length of the GI decreases until 40. Thus, the GI can be reduced to the length of the initial channel.

For a SISO system, the performance of the frequency domain TR-OFDM system is shown on Fig. 10. It can be noticed that for a GI length of L, the performance is equal to the performance in the ideal case for the time domain system. This result confirms that the two implementations are equivalent in terms of performance. Moreover, it confirms that the GI, when implementing TR in the frequency domain, can also be of length equal to the length of the initial channel.

Furthermore, the results obtained for 2 transmit antennas (see Fig. 11) confirm that the Time Domain TR-OFDM only requires a GI length equal to 40: the performance obtained with a length of 80 remains identical when decreasing the length to 40. The results also confirm the equivalence between the system with the implementation in the time domain and in the frequency domain as the BER performance match.

VI. CONCLUSION

In this paper, the way to combine TR with OFDM in a SISO system is presented and is shown to be very simple as the channel becomes purely real in the frequency domain. The receiver only requires a threshold detector in the case of QPSK symbols. This only comes with a pre-filtering at the transmitter side.

Moreover, the designing of a TR MISO system is straightforward and does necessitate any coding scheme as the contributions of every antenna will coherently add at the receiver side

Two different ways of designing the Guard Interval with their associated synchronization are presented and allow keeping the circularity of the channel while avoiding ISI: a double length Cyclic Prefix and a Cyclic Prefix with a Cyclic Suffix.

On the other hand, an advantageous and simple way of synchronizing the FFT window at the receiver side in a TR-OFDM system is shown by nullifying the phase of the channel at the receiver side.

Finally, this article shows that the Guard Interval in a TR-OFDM system that should be theoretically twice the size as the Guard Interval in a classical OFDM system, can have the same length as in the latter case, keeping thus the same spectral efficiency.

ACKNOWLEDGMENT

The authors would like to thank the French National Agency for Research (ANR) and the “Pole Images et Réseaux” (http://www.images-et-reseaux.com/en) for their funding through the TRIMARAN project (https://rd-project-trimaran.rd.francetelecom.com).

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