Time Reversal for Green Radio Communications

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Abstract—**In this article, Time Reversal (TR) signal processing techniques are studied and evaluated over novel realistic green use cases. The principles of Time Reversal and practical uses cases for green communications are designed considering Long Term Evolution-Advanced Coordinated Multi-Point transmission/reception (LTE-A CoMP), Fast Session Transfer (FST) extensions and multi-Radio Access Technology (RAT) architectures foreseen as promising green networks. Dedicated TR use cases are defined in order to identify limit and advantages of TR in a green radio context.**

Index Terms—**Time Reversal, Green Communications, Fast Session Transfer, Cooperative Multi-Point.**

I. Introduction

OVER the past few years, the carbon footprint of Information and Communication Technologies (ICTs) has grown. From 2% of global carbon emissions in 2007 it may reach 15% in 2025 as traffic demand grows exponentially while energy efficiency of network infrastructures is linearly increasing due to hardware natural improvement [1]. Therefore, interest for energy-aware (green) techniques is growing and Time Reversal (TR) has been identified as a good candidate for green communications [2].

An evidence of the burgeoning interest for green communications is the growth of energy-aware consortium and international projects such as GreenTouch [3], and EARTH (Energy Aware Radio and neTwork tecHnologies) [4]. GreenTouch is a consortium of international ICTs actors. Its mission is to deliver the architecture, specifications and roadmap needed to increase network energy efficiency by a factor 1000 from current levels. Similarly, international project EARTH goal is to significantly reduce the power consumption of cellular networks delivering different approaches applicable on component, node, and link levels.

In order to determine if TR is an efficient green wireless communication technique, theoretical gains are faced to link level simulations performed in relevant green scenarios. Dedicated use cases have been then defined and mapped on the novel realistic green scenarios of multi-Radio Access Technology (RAT) [5] that are promoted by French operator Orange in the GreenTouch consortium. The first scenario is the Long Term Evolution-Advanced Coordinated Multi-Point transmission/reception (LTE-Advanced CoMP) scheme [6], [7] which aims to reduce border-cell interference. The second scenario is an extension [8], [9] of the IEEE 802.1X Fast Session Transfer (FST) mechanism [10] which allows stations to transfer a session from a channel to another channel in the same or different frequency bands (2.4/5 GHz and 60 GHz) by considering different WLAN/WPAN air interfaces benefiting from Wi-Fi network backward compatibility. The third scenario is a multi-RAT heterogeneous network aiming to provide a seamless connectivity under power and Quality of Service (QoS) constraints considering a switching between independent networks using a Multiple Interface Management (MIM) utilizing inter-Medium Access Control (MAC) layer and dedicated multi-RAT Channel Quality Indicator (CQI) metrics. Such studies and results have been performed in the ICT-OMEGA (hOME Gigabit Access) project for the Home Networking [21][22].

The aim of this paper is to describe and evaluate TR benefits in the green communications context. The paper is organized as follows. Section II introduces TR principle and properties. Section III exposes novel uses cases for green communications turned towards convergent and heterogeneous networks. TR generic use cases are defined in section IV. Section V gives a propagation analysis carried out to predict advantages and limits of RT signal processing. A conclusion is drawn in section VI.

II. Time Reversal principle

TR is a signal processing technique adapted from the acoustic field [11] toward electromagnetic field [12]. It has been applied to Ultra-Wideband (UWB) systems [13] and, more recently, to narrow band communications systems based on non-impulsive waveforms [14]. A proof of the growing interest for TR applied to green communications is the project TRIMARAN: Time Reversal MIMO (Multiple-Input Multiple-Output) OFDM (Orthogonal Frequency Division Multiplexing) Green communications based on Micro Structured Antenna Arrays [15].

TR can be considered as a special case of beamforming pre-filtering technique and enables to focus waves in the temporal and spatial domain. TR spatial focusing property can be used to reduce interferences [16] and its time compression property simplifies the receiver complexity [17]-[20], thus, *using TR allows reducing both power emission and power consumption of systems.*

The TR principle lies in two steps: the *sounding* (fig. 1) and the *focusing* (fig. 2). The sounding step consists in an estimation of the impulse response of the multipath channel from the receiver to the transmitter. Then, the transmitter time reverses the Channel Impulse Response (CIR) and uses the result to pre-filter the signal. Electromagnetic waves re-experience the paths and add coherently at the target location.

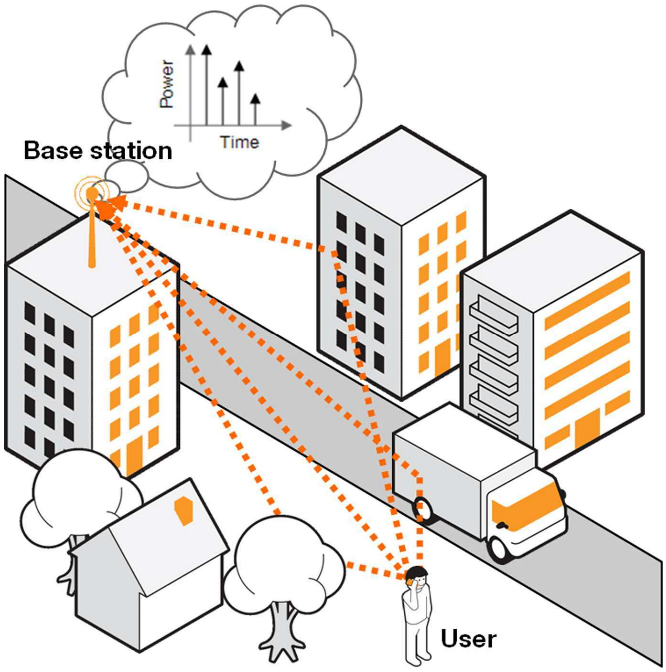

Fig. 1. Sounding step: the user sends a probe signal used by the base station to estimates the CIR.

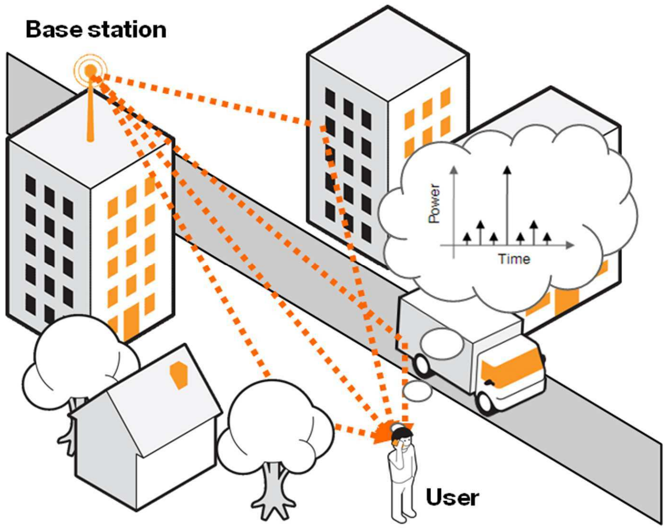

Fig. 2. Focusing step: the base station pre-filters the signal with a time-reversed version of the CIR. From the user side, the equivalent channel is then the autocorrelation of the CIR.

Let us denote $x(t)$ the transmitted signal, $y(t)$ the received signal, $h(t,\tau)$ the CIR where τ is the delay variable, $n(t)$ the Additive White Gaussian Noise (AWGN), τ_i the delay of path i and $*$ the convolution operation. Without TR, the received signal is expressed as follows:

$$\begin{aligned} y(t) &= x(t) * h(t,\tau) + n(t) \\ &= \sum_i x\big(t-\tau_i(t)\big) \times h\big(t,\tau_i(t)\big) \end{aligned} \quad (1)$$

The multipath propagation channel is expressed as a sum of echoes:

$$h(t,\tau) = \sum_i h\big(t,\tau_i(t)\big) \times \delta\big(\tau-\tau_i(t)\big) \quad (2)$$

The complex coefficient $h(t,\tau_i(t))$ is the gain the i^{th} echo of the baseband CIR of the propagation channel at the time t. When TR is used, the signal is pre-filter by $h^*(t,\tau_{max}-t)$, where * denominates the conjugate. Then, the received signal becomes:

$$y(t) = x(t) * R_h(t,\tau) + n(t) \quad (3)$$

where $R_h(t,\tau)$ is the instantaneous correlation function of the channel associated with the equivalent TR channel $h_{eq}(t,\tau)$ expressed as follow:

$$h_{eq}(t,\tau) = h^*(t,\tau_{max}-\tau) * h(t,\tau) = R_h(t,\tau) \quad (4)$$

The equivalent channel has then a peak which corresponds to the center of the autocorrelation function. Width of this central peak can be used to estimates the quality of the TR focalization properties.

III. Multi-RAT and convergent based use cases for green communications

The aim of green communications is to increase the energy-efficiency of ICTs. One way to achieve this goal is to reduce the complexity and transmission power of systems under QoS constraint, a convergent system should be able to switch toward the greenest technology available according to quality metrics. Switching mechanisms between different WLAN/WPAN interfaces and associated quality metrics to perform Multiple Interface Management are designed and evaluated in the project OMEGA (hOME Gigabit Access) [22] .Green communications uses cases extended to mobile radio communications and convergent indoor/mobile networks have been designed by Orange Labs [5] in the Green Touch consortium. These use cases are described below.

A. *LTE-Advanced CoMP*

Inter-cell interference is a recurring problem for wireless communications. LTE-Advanced CoMP is a radio-access technology intended to reduce border-cell interference: The station (eNode B) and Remote Radio Equipments (RREs) cooperate together on the downlink transmission in order to mitigate interference. It can be divided in two categories: Coordinated Scheduling / Coordinated Beamforming (CS/CB) and joint processing [23], [24] (fig. 3). Joint processing means that several eNode-B/RREs address the user (either with joint transmission or instantaneous cell selection) while with CS/CB a given station focus on the user while other stations try to null their interferences.

When beamforming is used the main lobe focus on the user, but secondary lobes can create interferences toward other users of the same cell. CS/CB intends to deal with this interference but it may be hard to perform perfect CS/CB with a high number of users. With TR, the focalization is not made toward the user location but at the user location and without secondary lobes. Therefore, the main benefit of Time Reversal applied to CoMP is to efficiently achieve spatial focalization without interferences toward other users.

Joint processing may benefit from the ability of TR to address a user even in a highly scattering medium and in Non-Line of Sight (NLOS) situation.

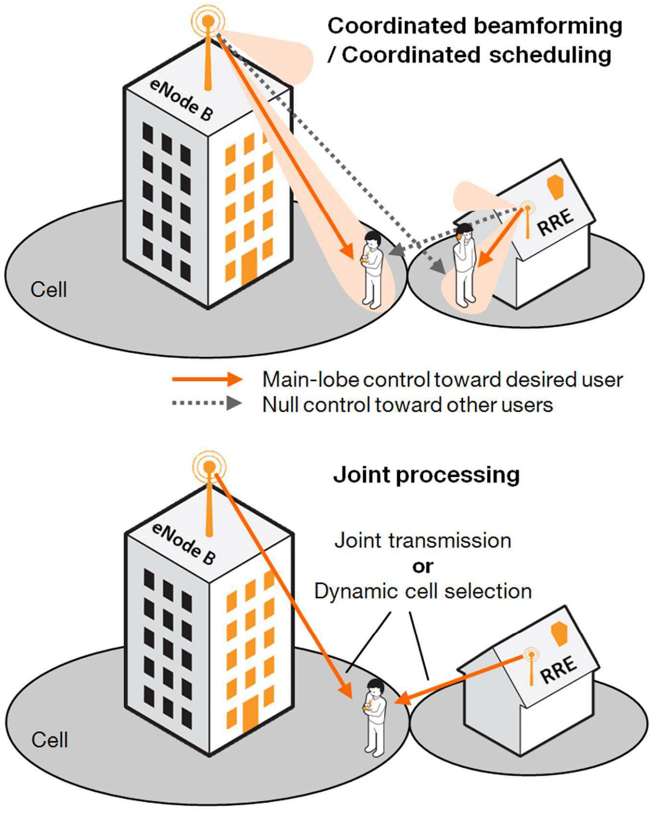

Fig. 3. Downlink CoMP transmission categories adapted from [6]. With CS/CB, stations null their interference toward other users while addressing desired user. With joint processing user can either use joint coherent/non-coherent transmission or make instantaneous cell selection.

B. Fast Session Transfer

Fast Session Transfer (FST) is a mechanism that allows a station to transfer a session from a channel to another channel in the same or different frequency band [10] by considering several Wi-Fi certified air interfaces. It can be applied to IEEE 802.1X systems in OBand (e.g., 2.4 and 5 GHz) and DBand (e.g., 60 GHz) if stations are multi-band capable. Stations can become noticeable, or not, for other stations by changing carrier frequency, FST can then be use to perform multi-hop relay and backhauling. This mechanism was first described within the IEEE 802.11ad standard [10] but compatibility with other IEEE802.1X systems (e.g., 802.15 or 802.16) is intended.

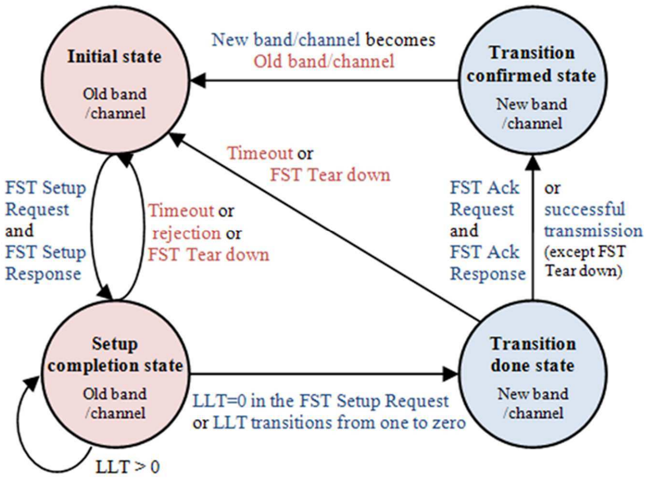

Fig. 4. States of the FST setup protocol.

Transition from one band/channel toward another band/channel is done according to the protocol defined in fig. 4. From the initial state, the stations exchange FST setup request and response. Once the Link Loss Timeout (LLT) reaches the value 0, stations operate a switch toward a new bandwidth/channel. If the switching if confirmed by acknowledgments (Ack), the transfer is completed. Fig. 5 shows an example of its utilization to target and lock a station at 60 GHz thanks to the 5 GHz range.

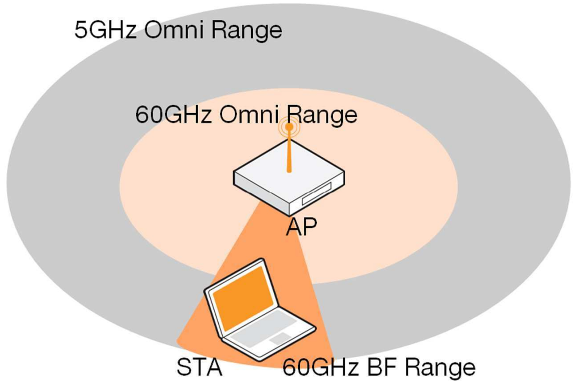

Fig. 5. An example of the use of FST: the station (STA) is located by the access point (AP) in the 5 GHz range, its location is then used to perform beamforming (BF) and reach it with 60 GHz technology.

As TR performance depends on the propagation channel, transmission bandwidth size and Radio-Frequency (RF) carrier, selection related to FST mechanisms may be efficiently combined with TR processing.

C. Simple and multi-RAT heterogeneous network

The last use case includes the previous ones. It consists in a simple and multi-RAT heterogeneous network. Given Channel Quality Indicators (CQIs), the network must be able to select the *greenest* access combination (access points, technology and modulation and coding scheme) under QoS constraints. Therefore, it must include CQIs evaluation mechanisms and switching protocols enabling seamless connectivity as investigated in the ICT OMEGA project.

LTE-Advanced CoMP can be viewed as a simple-RAT heterogeneous network where the best scheme of stations combination is selected to increase the Signal to Interference plus Noise Ratio (SINR) at the user location. FST is a switching protocol combining RF multi-band processing to MIM between Wi-Fi certified air interfaces.

IV. Generic TR use cases

This section is dedicated to the identification of limits and advantages of TR by defining TR use cases to be applied to multi-RAT and convergent use cases (cf. III). Impact of the frequency selectivity and bandwidth size, Doppler effect impact, antenna mismatch alignment, synchronization problems and number of transmission antennas are studied.

A. Frequency selectivity and Bandwidth size influence

The ideal TR equivalent CIR is the Dirac delta function. To strive toward this ideal case, the digital channel needs to have sufficiently uncorrelated taps. Additional taps can be seen as additional information about the user location and the more information we have about the user location, the more we can focus on it.

An easy way of getting this extra information is to increase the transmission bandwidth as it increases the resolution of the channel, i.e., the number of taps we can detect. Another way is to transmit over a highly scattering medium. Root Mean Square (RMS) delay spread τ_{RMS} is a common metric that quantifies the multipath richness of the medium. For a digital channel it can be expressed as:

$$\tau_{RMS} = \left[\frac{\sum_i (\tau_i - \tau_m)^2 \cdot G_i}{\sum_i G_i}\right]^{1/2} \quad (5)$$

where G_i is the average power of echo i and τ_m is the average delay of the channel given by:

$$\tau_m = \frac{\sum_i \tau_i \cdot G_i}{\sum_i G_i} \quad (6)$$

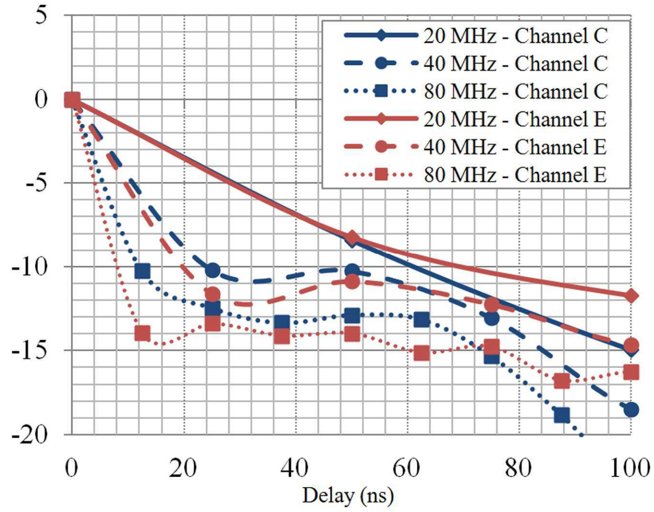

Fig. 6. First 100ns of the average delay profiles (in dB) of TGn channel C and E [25] with receiver synchronization on the central peak of the equivalent CIR.

On fig. 6 curves show that, for a given channel, focalization increases with transmission bandwidth. Moreover, focalization (i.e. first drop of the delay profile) is better with channel E which has a RMS delay spread of 100ns than with channel C which has a RMS delay spread of 30ns

Wide bandwidth and/or *high delay spread* (hence, high frequency selectivity) are then prerequisites to obtain good performances with TR as shown on fig. 6.

B. Doppler effect impact

One of the main drawbacks of TR is the need for slow channel variations. In order to get good performances, the *channel must remain constant* between the sounding and focusing step. If the *estimated* channel used for pre-filtering is outdated, the instantaneous correlation function becomes a cross-correlation instead of an autocorrelation and focalization properties are lost. A high Doppler effect will then induce strong uncorrelation between the estimated channel and the effective channel, causing a drop of performances.

As shown by fig. 7, if the system can estimates properly the CIR or if the channel variations are too fast, it is better not to use TR. Uncorrelated Time-Reversal means that the estimated CIR used for pre-filtering is outdated. Synchronization is made at the central peak location but as the CIR is outdated the main tap is no more at the peak location, the equivalent channel seems in NLOS propagation.

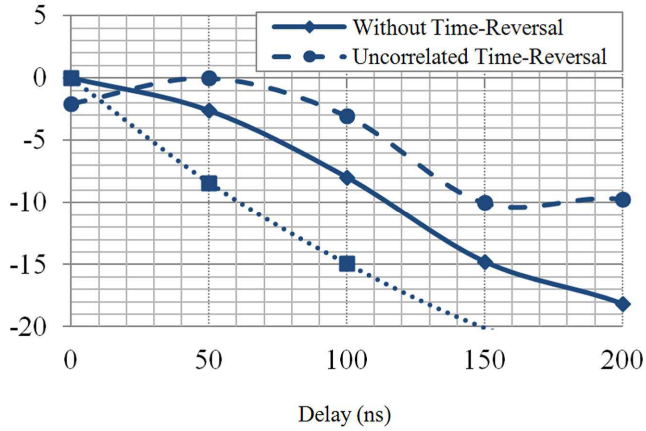

Fig. 7. Average Power Delay profile (in dB) of channel C with 20 MHz bandwidth.

C. Antenna mismatch alignment

Systems using directional antennas can suffer from mismatching, i.e. an unwanted transition from LOS to NLOS. With TR, this critical drop of performances can be avoided if FST is used to switch to a wider channel or a different carrier (with different propagation properties) when SNR drops.

D. Synchronisation problems

Ideally, systems using TR should synchronize on the central peak of the equivalent channel, thus, systems should be able to deal with the previous taps of the equivalent channel (e.g., to avoid interferences between consecutive OFDM symbols). Moreover, if the synchronization is biased, it can cause a drop of performance when the central peak of the equivalent channel is very sharp.

E. Number of antennas

In order to increase TR performances, it is also possible to *increase the number of transmit antennas* and to apply TR before each. The resulting equivalent channel is then the sum of the autocorrelation functions of the different CIRs between each transmit antennas and the receive antenna.

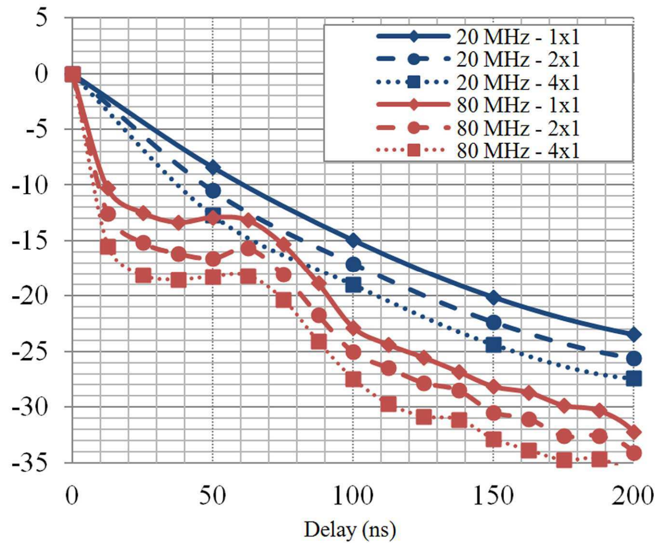

Fig. 8. Average Power Delay profiles (in dB) of channel C with 20 MHz and 80 MHz bandwidths for 1,2 and 4 transmit antennas and 1 receive antenna.

On fig. 8, curves shows that increasing the number of transmit antennas increases the focalization. The difference between the two first taps is increase but the remaining of the power delay profile is unchanged. Then, TR benefits from spatial diversity if channels are enough uncorrelated.

V. Propagation analysis

In order to evaluate benefits of TR, a comparison of TR performances is done through a propagation analysis of equivalent channels. We used IEEE 802.11 High Throughput (HT) and Very High Throughput (VHT) transmission modes of IEEE 802.11 standards [10], [26] over TGn propagation channel models C and E [25]. These models are valid for simulations with a communication bandwidth up to 40MHz. As we intend to simulate bandwidths up to 80MHz, we linearly interpolated TGn channels C and E. RMS delay spreads of channels stay unchanged: 30ns for channel C and 100ns for channel E.

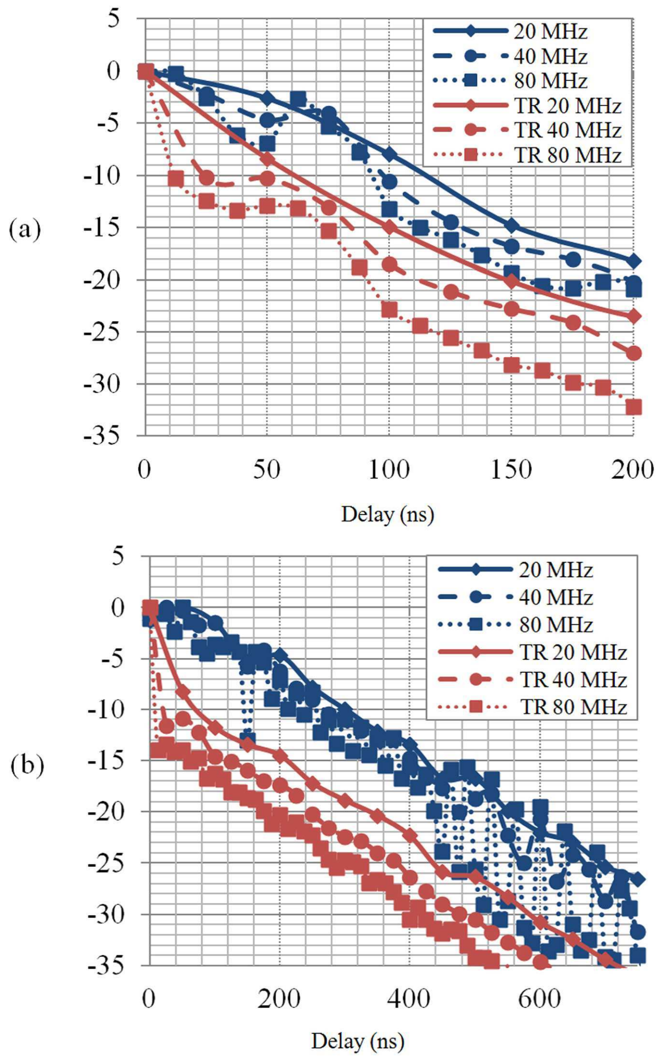

Fig. 9. Averaged Power Delay Profiles (in dB) of channels C (a) and E (b) for 20MHz, 40MHz and 80MHz bandwidths sizes.

As we can see on fig. 9, thanks to its focalization property which is in enhanced by bandwidth size, TR helps to increase the difference between the 2 main taps when the receiver synchronizes on the central peak. The main tap of channel E is not the first tap (as it is the case in NLOS situations), but when TR is used, if the receiver synchronizes on the central peak the multipath effect of the channel E is softened. Improvements are better with this channel which corresponds to a more scattering medium. This analysis corroborates the conclusions of part IV A: TR improvements are greater in a highly scattering medium and with a large transmission bandwidth.

VI. Conclusion

In this article we carry out a first analysis of benefits and limits of TR for green communications applied to Wi-Fi certified technologies. Practical Green use cases derived from Orange Labs contribution to GreenTouch were first exposed. Then we defined generic TR uses cases. Such cases can be mapped on the practical Green use cases in order to determine the benefits and limits of TR for green communication. A propagation analysis was also performed upon channels used upon WLAN/WPAN systems operating in 2.4/5 GHz bands with different channel bandwidth sizes, typically ranged from 20 MHz to 160 MHz.

The focalization property of TR allows interference reduction for LTE-Advanced CoMP and can simplify the addressing of selected user because the cancellation of interferences toward other users is inherent to TR. Moreover, its compatibility with highly scattering media can be use with FST to ensure a seamless connectivity even in case of antennas mismatching. TR improves systems robustness while reducing complexity of receiver thanks to its time compression property. Green communications can therefore highly benefit from TR. But we should however be careful with its utilization when transmission bandwidth is limited, or when the medium is not enough scattering. Moreover, if applying TR with a perfect knowledge of the channel improves performances of systems, a bad or outdated estimation of the channel can severely drop performances.

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