An Embedded Echo Cancellation Approach to DVB-T Gap-Fillers

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Abstract— **This paper explores a strategy for detecting and cancelling echoes produced in a DVB-T Gap-Filler and describes a way for its implementation in a low cost embedded system. First a general model of a Gap-Filler and its operation without echo cancellation is discussed. Then, we present a mathematical analysis for detecting and cancelling echoes from the autocorrelation of the OFDM signal. From this, the proposed echo cancellation strategy is implemented in a simulation model and tested in a Gap-Filler prototype.**

I. Introduction

To guarantee a full coverage of Digital Television signals, broadcasters are relying on the use of gap-fillers to complete the coverage in places where the signal is blocked by buildings or so severely attenuated that reception by the users has a very low quality of service. Gap-Fillers are usually small repeaters with normally less than 10W of power. Because of its small size it is very difficult to completely isolate the input and output signals giving rise to echoes in the output signal. Hopefully Digital Video Broadcasting - Terrestrial (DVB-T) [1] signals are well prepared to withstand large echoes and multipath signals thanks to the Coded Orthogonal Frequency Division Multiplexing (COFDM) modulation. However for the gap-fillers this also means a lower dynamic range at the output and, as a result smaller output power available and shorter range.

Therefore, echo cancellation is a very desirable feature of a gap-filler as it helps to increase the output power and thus the quality of the signal for a given distance range.

There are mainly two components of echoes in a gap-filler: multipath and feedback echoes. Multipath echoes are produced by the delay between signals from different transmitters, while feedback echoes are caused by insufficient antenna isolation. Both have a similar undesirable effect on the OFDM signal. To compensate this effect is necessary to introduce a Digital Signal Processing block inside of the gap-filler that implements a algorithm for echo detection and cancellation.

The performance of the Gap-Filler with echo cancellation will depend on how good is the estimation of the feedback channel (H_e in Fig. 1) and the speed of adapting the system to changes in the environment that can modify the feedback channel. According to the algorithms used, the channel estimation techniques are classified into four categories.

- *Pilot-aided methods* estimate the transfer function of the channel from a training sequence inserted in the transmitted signal and known by the receiver. However, because of the DVB-T standard does not define training sequences in the transmission, some alternative techniques [2]-[3], that insert their own training sequence in the receiver, have been developed. In these techniques, the OFDM signal received in the Gap-Filler is periodically interrupted for interspersing the training sequence among the data carriers. The downside of inserting a training sequence is that acts as an unwanted interference that would slightly degrade the OFDM signal.
- *Direct methods* [4]-[5] use the previous OFDM symbol, after being demodulated and decoded, to equalize the current OFDM symbol. These methods, apart from being very complex in hardware resources, introduce delay into the system (the one needed for decoding and encoding) that degrades the performance of the receivers.
- *Blind methods* do no require pilot carriers or training sequences. Blind methods take advantage of the statistical and structural properties of the signal to estimate the feedback channel. The correlation-based methods [6]-[7] are the blind methods most studied in OFDM systems. They exploit the periodicity of the cyclic prefix transmitted by OFDM symbols.
- *Semi-blind methods* [8] combine pilot-aided and blind methods to achieve better tracking of the channel.

In this paper we are going to study the problem of echo cancellation and address it by producing a solution technique for echo detection and cancellation, based on the statistical and structural properties (Blind method) of the DVB-T signal. Moreover, the solution proposed is a low cost hardware solution since it is not necessary to demodulate the OFDM signal, to generate training sequences or to implement additional signal converters for the echo cancellation.

II. DVB-T Systems

DVB-T systems are implemented in Single Frequency Networks (SFN) for good reception in mobile conditions. A SFN is a configuration of several transmitters operating in the same frequency to cover a target area. In OFDM systems, the maximum distance between transmitters should be established

taking into account the guard interval of the OFDM system in order to keep a high-quality and high-power signal. Ideally, the guard interval should be larger than the propagation time of the signal.

During the guard interval, the transmission of OFDM symbols is interrupted to avoid Inter-Symbol Interference (ISI) in the receiver. Therefore, larger guard intervals ensure more protection but reduce the data rate and the channel efficiency. In DVB-T, the guard interval is adjustable to 1/32, 1/16, 1/8 and 1/4 of a symbol period. For example in 8k mode, the guard interval can be $28\mu s$ (1/32), $56\mu s$ (1/16), $112\mu s$ (1/8) and $224\mu sec$ (1/4) corresponding to 8Km, 16Km, 33Km and 67Km of distance between transmitters.

Even though the guard interval is adjustable in a network design, the relatively high cost of the transmitters and their maintenance makes necessary the installation of Gap-Fillers to cover small areas where there are no signal or the signal is too weak to be decoded by the receivers. However, the transmission power of the Gap-Filler is limited due to the feedback echoes caused by the insufficient antenna isolation, as well as reflections in the ground and nearby objects. To improve the performance, this paper proposes a Blind Method to echo cancellation. The proposed method is analyzed in simulations and verified in a Gap-Filler prototype.

III. GAP-FILLER MODEL

The block diagram given in figure 1, represents a general model of a gap-filler. The input signal $x_D(t)$ is the TV signal reaching the gap-filler from the nearest repeater hence, we consider $x_D(t)$ the signal without echo we want to amplify and transmit to cover the shadow areas, $x_o(t)$ is the output signal of the gap-filler and $x_{RT}(t)$ is the signal with echo before of the cancellation. H_{SAW} is accounting for the filtering made by the receiver, notably analog filtering like the SAW filter that is selecting the channel being processed. H_{RT} is the digital filtering inside the echo canceller for eliminating the influence of adjacent channels. H_e is the response of the echo channel produced by the unwanted feedback. H_c is a group of delays and attenuations that is compensating the echo inside the gap-filler. H_F can be assumed to be a pure delay and the gain G_o controls the output power of the gap-filler.
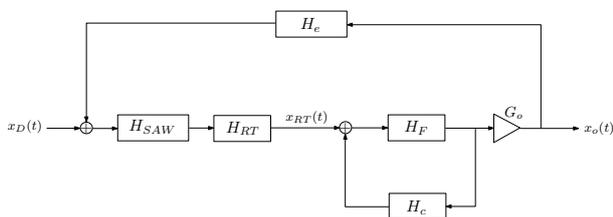

Fig. 1. Gap-Filler Model

Normally, the presence of echoes in a gap-filler causes a ripple in the frequency response of the output signal. The periodicity of the ripple will depend on the total delay of the echo, while its amplitude will depend on the coupling between the output and the input of the gap-filler. The echo

delay time is the sum of the response time of the chain, given by $H_{SAW} \cdot H_{RT} \cdot H_F$, plus the response time of the feedback channel, H_e. In real circumstances, the response time of feedback is much less than the response time of the direct chain, therefore, the ripple produced by the echo will have a characteristic frequency resulting from the delay caused by the gap-filler, and a small variation that hinges on the environment where the gap-filler is working.

A. Gap-Filler without echo cancellation

Let's assume that there is no compensation, $H_c = 0$, and the echo produced in the gap-filler model, given in figure 1, is exclusively due to coupling. The other echoes, such as multipath echoes have been omitted to simplify the analysis. The transfer function for our model is given by:

$$\frac{X_o}{X_D} = \frac{H_{SAW} \cdot H_{RT} \cdot H_F \cdot G_o}{1 - H_e \cdot H_{SAW} \cdot H_{RT} \cdot H_F \cdot G_o} \quad (1)$$

It is clear from equation above that if $|H_e \cdot H_{SAW} \cdot H_{RT} \cdot H_F \cdot G_O| \geq 1$ the gap-filler will be unstable. In a very simple case where the impulse response of the echo cannel is a pure delay with an attenuation, $h_e = \alpha \cdot \delta(t - \tau)$, the filters H_{RT}, H_{SAW}, H_F have all a unit response in all the frequency band, and the output gain $G_o = 1$, the above equation becomes:

$$\frac{X_o}{X_D} = \frac{1}{1 - \alpha \cdot e^{j2\pi f \tau}} \quad (2)$$

In this case the frequency response of the gap-filler has the characteristic ripple of the echo situations. For example, if $\alpha = 0.5$ the size of the ripple is almost 10dB peak to peak. This ripple limits the available range of the output power.

B. Gap-Filler with echo cancellation

If we include the compensation, H_c, in the analysis of our model, the transfer function of the gap-filler model becomes:

$$\frac{X_o}{X_D} = \frac{H_{SAW} \cdot H_{RT} \cdot H_F \cdot G_o}{1 - H_F \cdot (H_e \cdot H_{SAW} \cdot H_{RT} \cdot G_o - H_c)} \quad (3)$$

Therefore, to cancel the echoes in a gap-filler H_c must be equal to $H_e \cdot H_{SAW} \cdot H_{RT} \cdot G_o$. Taking into account that the frequency response of H_{RT} is completely known and that H_{SAW} can be approximately known by calibration. Then, it would be enough a good estimation of the echo delay, τ, and the attenuation, $Go \cdot \alpha$, to cancel an echo that consists only of a pure delay. However, this concept can easily be extended to the case where the echo channel, H_e, has several components. In that case, the system would have to estimate each of the delays and their respective attenuations to cancel completely all the echoes.

IV. Echo Detection

At first $H_c = 0$. If we suppose that Go=1 then, the signal before the compensation, $x_{RT}(t)$, is equal to the output signal of the gap-filler, $x_o(t)$:

$$
\begin{aligned}
x_o(t) = x_D * h_{SAW} * h_{RT} * h_F * (\delta(t)+ \\
h_e * h_{SAW} * h_{RT} * h_F+ \\
h_e * h_{SAW} * h_{RT} * h_F * h_e * h_{SAW} * h_{RT} * h_F + ...)
\end{aligned}
\tag{4}
$$

Assuming that $h_e(t)$ is small to guarantee a stable behavior, we can ignore the higher order terms of equation 4, and hence the autocorrelation of $x_o(t)$ becomes:

$$
\begin{aligned}
r_{xo}(t) = r_{x_D} * r_{h_{SAW}} * r_{h_{RT}} * r_{h_F} * [\delta(t)+ \\
r_{h_{SAW}} * r_{h_{RT}} * r_{h_F} * r_{h_e}+ \\
h_{SAW} * h_{RT} * h_F * h_e+ \\
h_{SAW}(-t) * h_{RT}(-t) * h_F(-t) * h_e(-t)]
\end{aligned}
\tag{5}
$$

In the above equation we identify three different terms. In a real gap-filler, the total delay of the echo, τ, is sufficiently large so that the three terms do not interfere each other, and the autocorrelation can be written:

$$
r_{xo}(t) = r^0_{x_{RT}} + r^\tau_{x_{RT}} + r^{-\tau}_{x_{RT}}
\tag{6}
$$

Each of the terms produces a peak in the autocorrelation. The first term represents the autocorrelation around $t = 0$, the one which gives the signal power. The second term represents the autocorrelation around $t = \tau$, where τ is the total delay of the echo, and the third term is the same as the last one but centered around $-\tau$.

As the cancellation process is made digitally in the discrete domain, the local peaks produced by the echo really are located around $n = N$ y $n = -N$, where N is the total echo delay in samples. However, the sampling frequency is not high enough and we cannot assume that N is the exact number of samples of echo delay, for this reason, we have to estimate separately the integer and the fractional part.

Taking advantage of the shape of the local peak, given by a sinc function, it is possible to determine the echo delay, N_D, from the known timing estimation expression using the values around N:

$$
N_D = r_{x_o}(N) + \frac{r_{x_o}(N-1) - r_{x_o}(N+1)}{2 \cdot [r_{x_o}(N-1) - 2 \cdot r_{x_o}(N) + r_{x_o}(N+1)]}
\tag{7}
$$

The integer part is directly the value of the autocorrelation in N while the fractional part is calculated by parabolic interpolation. The above equation is related with the total delay time τ by:

$$
\tau = \frac{N_D}{fclk}
\tag{8}
$$

Where $fclk$ is the sampling frequency.

V. Echo Cancellation

Once the echo is detected and the delay is known, the cancellation process is started. The compensation block H_c, given in figure 1, performs the cancellation process using multiple paths. Each path is considered as the grouping of two elements connected in series: a delay and an attenuation, allowing to compensate the effect of an echo in the gap-filler. Therefore, we could imagine the block H_c as an FIR filter of variable coefficients where each coefficient is represented by a path with its own delay and attenuation.

Let's study an iterative technique which utilizes the residual peak of the autocorrelation to estimate the value of the echo attenuation. This technique consists of a traditional PI control where the reference signal is the real attenuation α_{ref}, the output signal is the estimated attenuation α_{est}, and the error signal is the difference between the real and estimated signal $\Delta\alpha$.

It has been proven in simulations that the ratio between the peak autocorrelation in $n = 0$ and the local peak in $n = N$ is inversely proportional to $\Delta\alpha$. Accordingly, $\Delta\alpha$ can be obtained indirectly from the autocorrelation of x_o and α_{ref} can be estimated through an iterative process. So, α_{est} is given by:

$$
\alpha^i_{est} = \alpha^{i-1}_{est} + \Delta\alpha = \alpha^{i-1}_{est} + K \cdot \frac{r^i_{x_o(N)}}{r^i_{x_o(0)}}
\tag{9}
$$

The local peak of the autocorrelation and the ripple produced in the frequency response will be reduced as α_{est} is updated. The constant K establishes the speed to reach α_{ref}, however, a very high value of K may cause unstability in the gap-filler.

VI. Echo Tracking

Even in the case of fixed gap-fillers the characteristics of the echo are subject to changes with time: weather conditions, moving objects, nearby vegetation or new buildings can modify the echo parameters, thus the necessity of continuously tracking the echo. In our model, the function of the tracking process is to supervise the autocorrelation of x_o to detect new peaks or changes in existing peaks, and if necessary, uses a new path of compensation or updates the value of α_{est} as appropriate.

VII. Implementation of echo cancellation in an embedded system

Embedded systems provide solutions to specialized applications reducing their cost by means of the integration of the strictly necessary components. In addition, thanks to the programmable electronic, these systems allow updates without the need of hardware modifications. The above advantages make the embedded system an attractive option to implement the strategy of echo cancellation.

The figure 2 shows the proposed architecture for echo cancellation. The received signal in Radio Frequency (RF) is converted to Intermediate Frequency (IF) using a Local Oscillator (LO); in IF, it is filtered by SAW filter and amplified.

The signal from the ADC enters to the FPGA, where the echo cancellation is performed. Then, the signal digitally amplified goes through the DAC before being converted to RF, using the same LO. Finally, the signal is amplified by the power amplifier for its transmission. Our description focuses on the implementation of the process of cancellation made digitally, enclosed by dashed lines in figure 2.
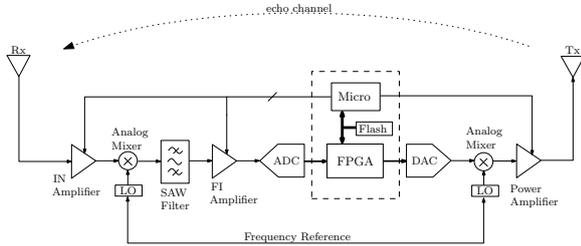

Fig. 2. Echo Cancellation Architecture

The Flash, the FPGA and the Microprocessor are interconnected through a 16 bits communication bus. The Flash memory of 16Mbit (1Mb x 16) is divided in three memory areas to store the loader, the FPGA program and the Microprocessor program. When the system is powered up, the loader controls the download of the FPGA program and the start of the Microprocessor program.

In the FPGA, the 16 bits communication bus is connected to Register Bank (Figure 3) to allow data exchange between the FPGA and the Microprocessor. The Register Bank of the FPGA is seen by the Microprocessor like an external RAM, where each memory address corresponds to a specific register. In total, there are more than 60 registers to control the blocks implemented in the FPGA.

A. FPGA

A Spartan-3A DSP 1800 FPGA is used for the Gap-filler prototype. The blocks implemented in the FPGA are shown in figure 3, all blocks are connected to the register bank so they can be controlled from the microprocessor by the communication bus.
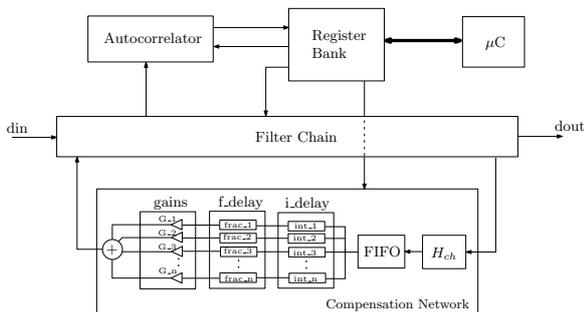

Fig. 3. FPGA architecture

Analyzing the blocks implemented:

- In the Filter Chain, the signal from the ADC goes through a bandpass digital filter that selects the band of interest.

- The Compensation Network, shown in figure 3, implements the H_{ch} filter which compensates the effect of the SAW and H_{RT} filters, and the delays and attenuations to compensate the echo channel.

  The compensation of the echo channel consists of 4 modules: the module *FIFO*, delays the output signal a fixed number of clock cycles, the same for all paths. Then, the signal is delayed by *i_delay* an integer number of clock cycles, different for all paths. In *v_delay* an interpolator implements the fractional delay and *gains* attenuates the delayed signal. Finally, all the paths are summed and the result is the compensation signal.

- The autocorrelator performs the 1024 points FFT - IFFT sequentially using the same hardware to obtain the autocorrelation of the signal. This block is started from the microprocessor. When the autocorrelation finishes, the control block sets a flag to notify the microprocessor of this event. Also, is possible to accumulate several autocorrelations to reduce the effect of noise. The result of the accumulated autocorrelations is stored and can be accessed by the register bank.

- The Register Bank is an internal memory space inside of the FPGA, where the data of the autocorrelation and the parameters of the control of all blocks are stored. Each of the registries can be accessed and modified from the microprocessor in real-time.

B. Microprocessor

The Microprocessor used in the Gap-Filler prototype is a ARM7TDMI-S of 32-bit with 64KB RAM. Its main functions are to process the data of the autocorrelation for the echo detection and cancellation, and to adjust the amplifiers for Automatic Gain Control (AGC) of the Gap-Filler.

In the proposed architecture, the Flash and the Register Bank of the FPGA are connected to the microprocessor via the External Memory Control Module (EMC), while the general-purpose lines are used for controlling the amplification stages of the gap-filler. In the startup, the loader downloads from the Flash Memory, critical parts of program code in the internal RAM of the Microprocessor to avoid bottleneck in the communication bus and therefore, to improve the response time of the echo canceller.
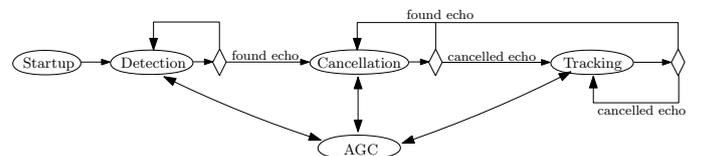

Fig. 4. Global state machine

The algorithm of cancellation runs on the CMX Real-Time Multi-Tasking Operating System and it is consists mainly of four state machines. The diagram given in Figure 4 shows the global state machine that controls the program flow.

The *AGC* state is a parallel task to the cancellation process that constantly monitors the signal levels and, if necessary

modifies the gain of the amplifiers. The states *detection*, *cancellation* and *tracking* are sub state machines responsible for carrying out the cancellation strategy.

- In the *detection* state, the Microprocessor starts the autocorrelation block of the FPGA and then, its result is read through the Register Bank by the Microprocessor to determine if there are echoes. When an echo is found, the *global* state is notified, otherwise the system continues looking for echoes in the result of the autocorrelation.

- Once the *cancellation* state is initiated, the microprocessor accesses to Register Bank to estimate the echo delay (equation 7) and the echo attenuation (equation 9). The attenuation estimation is based in an iterative process, therefore, the echo will be reduced progressively as the attenuation estimated converges. When the echo is too small that the ripple produced in the frequency response is negligible, the software interprets that the echo has been cancelled and the *global* state is notified.

- The *tracking* state will started provided that all the echoes have been canceled. In this state, the software monitors the result of the autocorrelation to initiate the *cancellation* state when an existing echo has been modified or a new echo has been detected.

VIII. RESULTS

A. Simulation Results

The model of Gap-Filler with echo cancellation has been implemented in Simulink using a clock frequency of 36MHz. The total delay introduced by the signal processing in the Gap-Filler is 200 samples, 5.55 μs approximately, and the time taken by the autocorrelation block to produce just one autocorrelation is 350 μs. Analyzing the Simulink model equivalent to the model given in Figure 1:

- The DVB-T input signal with 8MHz bandwidth is generated by a MatLab script.
- The variable group delay of the SAW filter has been modeled as an allpass filter. This filter has a average delay of 12 samples.
- The H_{RT} filter is a passband FIR filter of 169 taps.
- H_F is a pure delay that delays the signal 104 samples for simulating the delay produced by the rest of the gap-filler.
- H_e is an FIR filter that simulates the feedback channel.
- The compensation block H_c consists of several sub-blocks that perform the echo detection and cancellation. The autocorrelation is obtained by the Simulink Autocorrelation Block while, the state machines, described in the section VII-B, are implemented in C-code by the Simulink S-functions.

The figure 5 shows the ripple produced in the output signal of the Gap-Filler for different values of coupling. The mean ripple is calculated as the RMS value of the oscillation produced in the frequency response of the output signal.

In simulations, it has proven that to detect the echoes with mean ripple peak to peak of 1dB, it is necessary to accumulate at least the result of 64 autocorrelations.
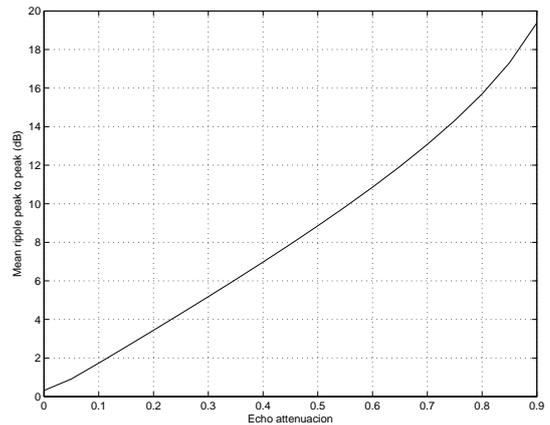

Fig. 5. Mean Ripple in the output of the gap-filler

The figures 6 (a) and (b) show the mean and standard deviation of the delay error for different values of Nsym, where Nsym is the number of accumulated autocorrelations. The delay error is calculated as the difference between the real delay and the estimated delay. The real delay is produced by Variable Fractional Delay Block of Simulink that delays the signal a fractional number of samples using linear interpolation while, the estimated delay is calculated from the equation 7. In this simulation the feedback channel is considered as a pure delay with a coupling factor of 0.5 ($\alpha \cdot G_o$).
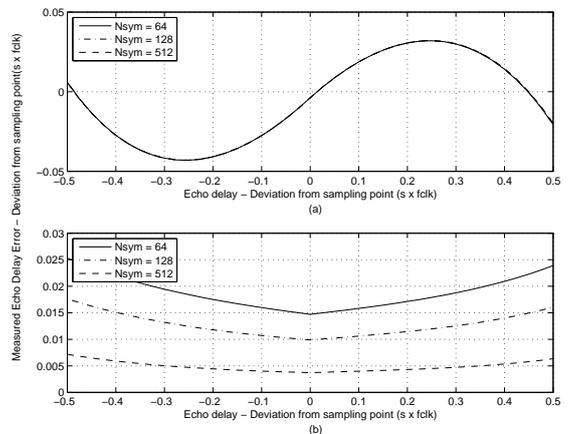

Fig. 6. (a) Echo Delay Error Mean
(b) Echo Delay Error Standard Deviation

The delay error mean, shown in the figure 6 (a), is the same independently of the number of accumulated autocorrelations, whereas, the delay error standard deviation, shown in the figure6 (b), is reduced as the number of accumulated autocorrelations is increased. Nevertheless, in any case the maximum errors occur when the deviation from sampling point is ± 0.25 samples.

The response time of the echo canceller is defined as the time needed to reduce 90% of the initial echo. The figure 7 (a) and (b) show the response time of the echo canceller and
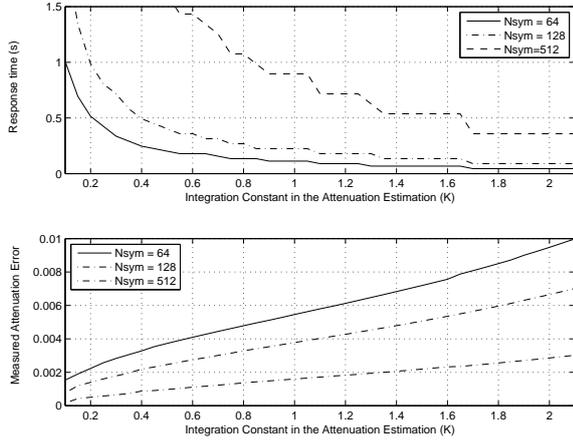
Fig. 7. (a) Response time of Echo Canceller
(b) Attenuation Error Standard Deviation

the attenuation error standard deviation for different values of K in the attenuation estimation (equation 9). A echo channel formed by a pure delay without deviation from sampling point and a coupling factor of 0.5 ($\alpha \cdot G_o$) is considered in the Simulink model.

The higher the value of K, the response time of echo canceller is smaller. However, as K increases the attenuation error may cause unstability in the system.

In the worst case, when the deviation from sampling point is 0.25 samples, the delay error mean is approximately 0.045 samples. Therefore, if the maximum delay error is considered as the sum of the delay error mean plus two standard deviation then, the simulation results with echo cancellation are shown in figure 8.
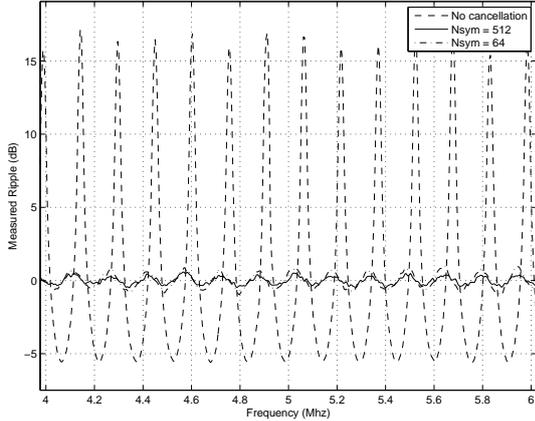

Fig. 8. Ripple in the output of the gap-filler

In the figure 8, the ripple without echo cancellation is produced by a coupling factor of 0.9 ($\alpha \cdot G_o$) and has a peak to peak ripple of 20 dB. In the other cases with echo cancellation, the peak to peak ripple is reduced to around 0.7 dB when Nsym=64 and to 0.4 dB when Nsym=512.

B. Laboratory Test Results

In order to verify the results obtained in the simulations, a Gap-Filler prototype has been implemented and tested. The input signal to the Gap-Filler (OFDM signal with 8MHz bandwidth, 50dBμV power, 64-QAM constellation, 474MHz RF Output, guard interval 1/16 and 8K mode) is generated by an OFDM modulator. In the Gap-Filler, the received signal in RF (474MHz) is converted to IF (36MHz) using a local oscillator and then, passes through a SAW filter that selects the desired channel DVB-T. The signal is digitized for echo cancellation and finally converted back to RF before being amplified and transmitted.

The digital signal processing is performed by a Spartan-3A DSP 1800 FPGA and a ARM7TDMI-S of 32-bit. A strong bandpass filter of 169 taps eliminates the Adjacent Channel Interference (ACI) and four paths with programmable gains and delays are used in the compensation network to compensate the effect of the feedback channel.
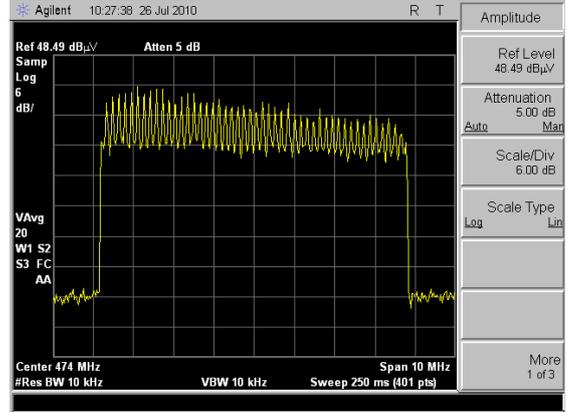
(a) Output spectrum without echo cancellation
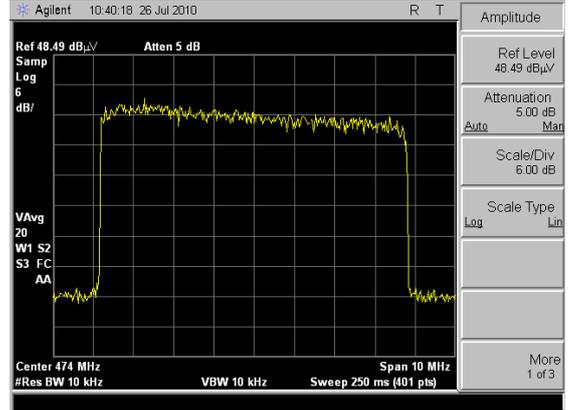
(b) Output spectrum with echo cancellation

Fig. 9. Output spectra of the Gap-Filler prototype

The Figure 9 shows the output spectra of the Gap-Filler in the channel 21 (470MHz - 478MHz) with and without echo cancellation. As been in Fig. 9(b), the ripple produced by the feedback echoes is significantly reduced, allowing greater transmission capacity and ensuring system stability.

In laboratory tests, feedback echoes +6 dB greater in power that the input signal were suppressed keeping the system stable.

IX. Conclusions

In this paper we have studied the effect of the echoes in a Gap-Filler and we have proposed an low cost hardware architecture to implement the echo cancellation strategy in an embedded system.

Using the echo cancellation, the mean ripple produced in the frequency response of the Gap-Filler output can be reduced by over 90%, the number of echoes that could cancel the system will depend on the paths implemented in hardware and the maximum echo delay that can be detected and cancelled is $15\mu s$.

The more autocorrelations are accumulated, the error in the estimation of the echo channel is smaller, but the response time of the system increases. To work in a safe environment without danger of the system becoming unstable it has been deduced that the K parameter should be $K < 2$. To guarantee a rapid response of the system (which is also helpful for maintaining the stability) the system must work with the highest possible value of K. For example, a $K = 1.8$ produces a response time to echo changes of $0.1s$ while keeping a reduced ripple at the output. That means that time varying echoes should change with a frequency of less that 1 or 2 Hz.

Therefore, the echo canceller parameters should be set according to the specific needs for the environment where the gap-filler is working.

References

[1] *Digital Video Broadcasting(DVB); framing structure, channel coding and modulation for digital terrestrial television*, European Telecommunications Starndards Institute (ETSI), EN 300 744 V1.6.1 (01-2009).

[2] K. M. Nasr, J. Cosmas, M. Bard, and J. Gledhill, "An Echo Canceller for DVB-T/H On-Channel Repeaters," *IEEE Trans. on Vehicular Technology*, pp. 639-643, April 2007.

[3] M. Mazzotti, F. Zabini, D. Dardari, and O. Andrisano, "Performance of an Echo Canceller based on Pseudo-Noise Training Sequences," *IEEE Broadcast Symposium*, Alexandria(VA), USA, October 2008.

[4] K. Fazel and S. Kaiser, *Multi-Carrier and Spread Spectrum Systems*. John Wiley & Sons Ltd, 2003.

[5] S. I. Park, H. Eum, S. R. Park, G. Kim, Y.-T. Lee, H. M. Kim, and W. Oh, "Novel equalization on-channel repeater with feedback interference canceller in terrestrial digital multimedia broadcasting system," *ETRI Journal, vol. 31, no 4, pp. 357-364*, August 2009.

[6] Y. Zeng and T. S. Ng, "A proof of the identifiability of a subspace-based blind channel estimation for OFDM systems," *in Proc, of the IEEE Personal, Indoor and Mobile Radio Communiactions*, vol. 2, pp. 1105-1108, September 2003.

[7] A. Wiewiorka and P. Moss, "Digital on-channel repeater for DAB," *BBC R&D White Paper WHP120*, September 2005.

[8] T. Cui and C. Tellambura, "Semiblind channel estimation and data detection for OFDM systems with optimal pilot design," *IEEE Trans. on Comm.*, vol. 55, no. 5, pp. 1053-1062, May 2007.