OFDM Reception Algorithms for SFN

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***Abstract*— In this paper, we analyze the impact of single frequency networks on the design of an ISDB-T receiver. We focus on challenges faced during the phases of symbol timing synchronization and equalization. Results in literature show that the challenges stem from the length of the channel impulse response and that opportunities to improve performance are found by exploiting the sparsity of the channel in the time domain. We conclude by showing the results of tests run on the prototype that resulted from this study.**

***Keywords*— TV receivers, Digital TV, ISDB-T, SFN**

I. INTRODUCTION

Since its beginning, Digital Television broadcasting services have been in wide adoption, having replaced Analog Television initially in countries like USA and Japan and gaining popularity throughout the world. In Brazil, Digital TV has reached 46% of the households [1] and the Analog switch off for the central urban areas is currently scheduled to 2015 with the complete nation-wide switch off scheduled to 2018 [2].

Idea! Electronic Systems [3] develops innovative products for the Digital TV market as a provider of Licensable Intellectual Property (IP) and Design Services for the Semiconductor industry with focus on Telecommunication and Digital TV systems. Its portfolio includes IPs for transmitters and receivers, covering the three broadcast mediums (terrestrial, satellite and cable) and multiple standards.

These IPs are used in commercial products, including FPGA-based professional equipment, DSPs (Digital Signal Processors) and ASICs (Application Specific Integrated Circuits), with one of the most relevant of these products being the ISDB-T demodulator ASIC ID-DTV01 [4], developed in partnership with Eldorado Research Institute [5].

This article presents some of the results found during the internal R&D studies developed by Idea!'s signal processing algorithms team and is organized as follows: Section II gives a brief introduction to the ISDB-T standard, with highlights to its key parameters and features; Section III describes some of the challenges for reception under single frequency network (SFN) conditions and presents and explores a number of possible solutions. A few chosen implemented solutions, simulations and FPGA-prototype lab tests results are presented in Section IV. In Section V the final conclusions are made, with acknowledgments in Section VI.

II. THE ISDB-T SYSTEM

Digital Terrestrial Television Broadcasting (DTTB) services using ISDB-T started in Japan in December 2003. The ISDB-T system was developed by the Association of Radio Industries and Businesses (ARIB) [6], [7].

ISDB (Integrated Digital Services Digital Broadcasting) is a type of Digital broadcasting intended to provide audio, video, and multimedia services, with ISDB-T being the terrestrial broadcast standard. Since the ISDB was developed to cover many different services, it offers a wide variety of transmission and configuration parameters to meet each service's requirements.

Brazil has also adopted ISDB-T transmission system as base for its DTTB services in December 2007. Before adopting ISDB-T, the Brazilian Ministry of Communications led a study group composed of several universities, R&D centers and local broadcast industry and manufacturers in order to establish a Brazilian Digital TV standard. The study analyzed and compared technical aspects of the existing Digital TV standards, as well as reception performance in different scenarios and devices. After several tests [8], [9], ISDB-T showed the best results and was chosen to be implemented in Brazil.

However, the Brazilian standard, called ISDB-Tb or SBTVD (*Sistema Brasileiro de Televisão Digital*), features some differences from its parent standard, the Japanese ISDB-T. ISDB-Tb adopts MPEG-4 video coding system (instead of MPEG-2), different transmission spectrum mask, receiver IF frequency and field frequency for one-segment service (mobile reception for Digital TV broadcasting service). It also adopts GINGA (Brazilian data casting system) and SBR (Spectral Band Replication) for audio coding [10].

The ISDB-T, like DVB-T, uses orthogonal frequency division multiplexing (OFDM) modulation scheme. While DVB-T uses COFDM (Coded-OFDM), ISDB-T uses Band Segmented Transmission-OFDM (BST-OFDM), and it consists of 13 OFDM segments in a 6 MHz transmission channel bandwidth.

The OFDM modulation scheme allows a very efficient use of allocated frequency band because subcarriers are orthogonally arranged in the frequency domain. Moreover, in ISDB-T, the OFDM is made robust to multipath fading by the addition of a cyclic prefix (also known as Guard Interval). It supports four Guard Interval (GI) length configurations (1/4, 1/8, 1/16 and 1/32). However, as a cyclic prefix, it adds redundant information, decreasing the information bit rate.

The ISDB-T standard provides three transmission modes (Modes 1, 2 and 3), each having different carrier intervals. In Mode 1, one symbol consists of 2048 carriers, while Mode 2 has 4096 and Mode 3, 8192 carriers.

Four digital modulation schemes are possible (DQPSK, QPSK, 16QAM, and 64QAM) to allow flexible transmission rates.

ISDB-T also provides concatenated error-correcting codes: Reed-Solomon (204, 188) coding scheme for the outer code and a convolutional code for the inner code. The convolutional coding is a 1/2 rate code with several supported puncturing patterns configuration (2/3, 3/4, 5/6 and 7/8) to obtain different coding robustness.

Frequency-domain and time-domain interleaving are proposed in the standard, generating permutations between symbols to spread them over OFDM frames in time and segments in frequency. It also applies bit and byte interleaving, which spread the data information stream over different carriers to avoid corruption of consecutive bits caused by selective fading.

Hierarchical transmissions of up to three layers (Layers A, B, and C) are supported in ISDB-T. The transmission parameters can be changed in each of these layers.

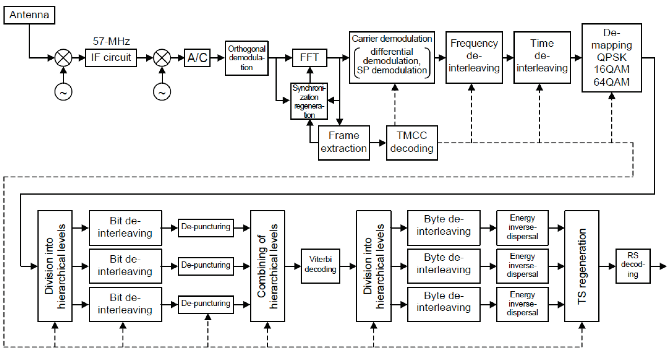

Fig. 1. Outline of a receiving block diagram

At the reception end, an ISDB-T demodulator requires several error correction blocks to deal with non-ideal transmission environment. Figure 1 illustrates the desirable block diagram of a receiver [11].

As can be seen in Figure 1, both time-domain and frequency-domain information are used to correct these errors ("Synchronization regeneration" block). These errors can be classified into three major groups: carrier frequency offset, sampling frequency offset and symbol timing offset. Carrier and sampling frequency offset are the differences in the carrier frequency and in the sampling clock between the transmitter and the receiver. Symbol timing offset is the difference between the actual carrier that starts an OFDM symbol and the estimated carrier in the receiver side.

III. Case study: Single Frequency Networks

Traditionally, radio and television networks have been structured to have a single transmission tower per town, each with its signal occupying a certain frequency band licensed for that area. In general, the same network uses different frequency bands from one town to the next, forming what is known as a multiple frequency network (MFN). In MFNs, receivers near obstacles such as mountains and skyscrapers or at the edge of coverage areas usually have difficulties since in such places the signal arrives with very low power.

Single frequency network (SFN), an alternative type of network deployment for digital radio and television, can bring significant gains in power efficiency and coverage area while dealing with some of the issues of MFNs. It consists of multiple transmission towers that broadcast the same signal in the same frequency band serving a large region: large metropolitan areas, groups of towns or even an entire country. The presence of many transmission towers with less power scattered across a region, as opposed to one large high-power transmitter, increases the chance that a given receiver will have access to a strong signal, be it from a nearby tower or several more distant towers.

The more obstacles to the signal propagation a region has, the more it benefits from SFNs. In dense urban areas, it is usual for the paths between a central television transmitter and receiver to be obstructed by tens of buildings. Mountainous terrain is also a frequent cause of bad signal reception. In fact, it is shown that even regions without severe obstacles are more evenly covered when served by SFNs. In [12], field tests and measurements are made in the area of Ghent, Belgium, and [13] describes the gains obtained by the SFN in the Shanghai, China, metropolitan area.

Single frequency networks pose some challenges, especially to the reception. The presence of signals coming from different transmitters, and therefore having different propagation delays, generates channels with significantly long impulse responses. For this reason, the delays between the signals being transmitted by each tower should be calculated carefully, at a minimum to guarantee that the impulse responses will not be longer than the cyclic prefix at most receivers (thus avoiding ISI). In [14], [15], [16], [17], several techniques are discussed pertaining to the placement and relative delays of the transmitters in SFNs. However, in spite of such efforts, receivers will still have to deal with longer channel impulse responses (CIR) caused by the inherently different propagation distances.

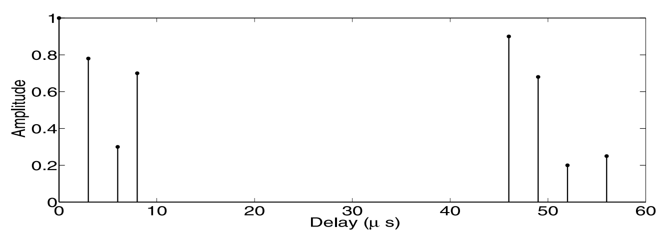

Fig. 2. CIR of an SFN channel consisting of two channels with exponential power-delay profiles.

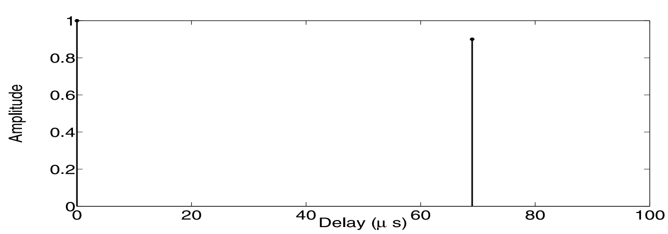

Fig. 3. CIR of an SFN channel consisting of two single-tap channels.

The CIR in scenarios with SFN can be modeled as the combination of two or more typical models of wireless CIRs (such as Rayleigh or Rician channels) with a different delay for each. Examples of such CIRs are shown in Figures 2 and 3. We can see in Figure 2 that the signal transmitted by each tower propagates through a channel with line of sight and an exponential power-delay profile. A different model is shown in Figure 3, where each of the two received signals has only one propagation path. This model is usually found in testing standards such as [18] and will be used in this paper due to its simplicity and similarity with more realistic models. We hereinafter refer to it as the SFN channel model. The delays between the signals coming from each transmitter are determined by the relative delays of the transmitted signal, both deliberate and unintentional, as well as by the different propagation times.

The challenges imposed by SFNs on receivers arise from the peculiarities of the CIR, which affect all synchronization and equalization. In this paper, we focus on OFDM symbol timing synchronization and on channel estimation for equalization.

A. Symbol Timing Synchronization

As mentioned earlier, the ISDB-T standard adopts Orthogonal Frequency-Division Multiplexing (OFDM), in which the data stream is parallelized and transmitted in blocks (called OFDM symbols), after the inverse discrete Fourier transform (IDFT) of the block is computed. In ISDB-T, each OFDM symbol is preceded by a cyclic prefix. In such systems, receivers are required to estimate the symbol start in order to avoid intersymbol interference, or ISI. The process of symbol timing synchronization should supply the receiver with an accurate estimate of the first sample to contain information of each OFDM symbol.

The use of SFN affects symbol timing synchronization significantly. Depending on relative distances, delays and transmit powers, it is possible to have a CIR in which the earlier taps have less power than some in the middle or at the end of the CIR. Note that, in order to avoid ISI, the reference for the start of the symbol must be the earliest copy of the signal to arrive (that is, the first tap in the CIR), not the one with the highest power.

It is possible to divide timing synchronization into coarse and fine synchronization, where the coarse algorithm should provide an estimate that is "precise enough" for the following few steps in the reception to work, up to the point where the fine timing synchronization algorithm is run and a precise estimate is obtained. The fine estimation is run periodically so as to keep track of this parameter. This division is adopted in [19], where the received signal is used in the time domain for the coarse estimation and in the frequency domain for fine estimation.

Coarse estimation of the start of the OFDM symbol is made in [19] as the maximum of the autocorrelation of the received signal, as described in

$$\hat{n} = \arg\max_{n} \left| \sum_{i=n}^{n+N_{cp}-1} r(i)\, r(i+N) \right| \qquad (1)$$

where $r(i)$ is the i-th sample of the received signal r in the time domain, N_{cp} is the length of the cyclic prefix and N is the size of the discrete Fourier transform (DFT). Indeed, expression (1) corresponds to the sample autocorrelation between $r(i)$ and $r(i+N)$ through a window of size N_{cp}, so that it reaches its peak when the entire window contains the cyclic prefix.

In Figures 4 and 5, we show the autocorrelation as calculated in (1) for two different channels: the additive white Gaussian Noise (AWGN) channel and the aforementioned SFN channel model. Notice that in Figure 4, there is a single well-defined maximum marking the position of the starting sample of the cyclic prefix. Channels with short power-delay profiles and whose largest tap concentrates most of the power have similar curves for their autocorrelation. Figure 5, on the other hand, depicts the autocorrelation of the SFN channel with two equally large taps and a delay corresponding to 50% of the length of the cyclic prefix. Notice that the autocorrelation curve has a significant plateau, and the maximum can be located at any point on it, depending only on the noisy measurements of the sample autocorrelation. In this case, as we see in Figure 5, that the correct start of the cyclic prefix is at the corner point, at the beginning of the plateau, and the maximum is over 100 samples to the right. If we were to use this estimate, the ISI might be strong enough to make the subsequent synchronization algorithms significantly less accurate.

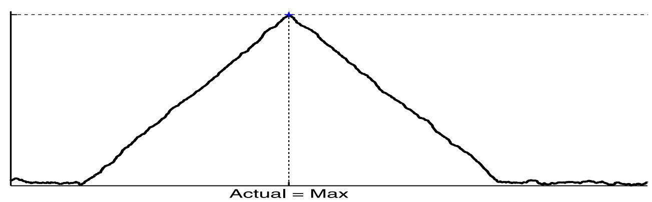

Fig. 4. Autocorrelation as in (1) for an AWGN channel

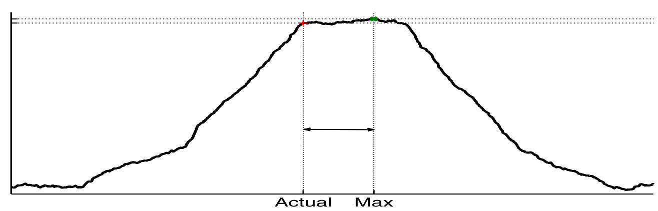

Fig. 5. Autocorrelation as in (1) for an SFN channel

In [20], a method is proposed to estimate the start of the OFDM symbol based on the derivative of the autocorrelation in (1). The idea is that the first inflection towards a smaller slope in the autocorrelation happens at the start of the OFDM symbol. Since derivatives amplify high-frequency noise, the paper proposes that the derivative be followed by a low-pass filter. In [21], a new filtering technique is proposed for the derivative approach, and its results show significant improvement. In [22], a different approach is proposed, based on the triangular shape of the autocorrelation and the assumption that the channel would not have more than two significant taps. Our tests indicate that these approaches are highly sensitive to the noise in the sample autocorrelation, although further filtering is enough for these algorithms to perform with satisfactory accuracy.

SFN channels also affect fine symbol timing estimation, which is usually performed after the DFT and is based on the pilot signals. In [23], the authors use the DFT property that a shift in the time domain corresponds to a linear phase in the frequency domain to argue that the synchronization error is proportional to the derivative of the phase of the estimated channel frequency response (CFR). Note, however, that the derivative of the phase of the CFR corresponds to the synchronization error only for AWGN channels, but the two values differ significantly for SFN channels. In fact, for SFN channels with two equal taps, this approach returns an estimate exactly in the midpoint between the two taps. Thus, this approach is not well-suited for SFN.

A more accurate approach for SFN channels is proposed in [24], where the authors derive the maximum likelihood estimate from the CIR, which is obtained by taking the IDFT of the estimated CFR. This approach produces accurate estimates, at the cost of a significant increase in complexity from the periodic computation of the IDFT.

Therefore, SFN channels require more complex symbol timing synchronization techniques that take into account the presence of multiple taps with similar power and long delays.

B. Equalization

OFDM systems have the advantage of making the equalization process less complex when compared to its single-carrier counterparts. In fact, as long the the CIR is shorter than the cyclic prefix, equalization is performed by dividing the received signal at each subcarrier by its corresponding channel gain, a process that requires the estimation of the CFR at the subcarriers. In this section, we discuss different channel estimation methods for situations in which the CIR length is close to that of the cyclic prefix.

The ISDB-T standard defines that pilot signals must be transmitted in all OFDM symbols, one for every 12 subcarriers, starting from the first, fourth, seventh or tenth subcarrier [7]. In addition to these scattered pilots, the last subcarrier will always contain a continuous pilot.

The gains at pilot subcarriers can be obtained directly while those in data subcarriers can be estimated via interpolation. When the interpolation is performed across time as well as frequency, 2-D interpolating filters can be used, as derived in [25], where the minimum mean square error (MMSE) channel estimate is obtained. Such 2-D approaches are prohibitively complex and do not result in significant performance gain in static scenarios with little CFR variation in time.

In scenarios where constant CFR can be assumed, the pilots can be combined in groups of four OFDM symbols in order to have one pilot at every three subcarriers, thus increasing the maximum CIR length, according to the Nyquist-Shannon sampling theorem [26]. We should note that grouping the pilots in this manner might generate distortions even when the CFR is constant if sampling clock offsets or carrier frequency offsets are not correctly compensated, since these offsets will cause differences in CFR phase between OFDM symbols.

Frequency-domain channel estimators can be devised according to the MMSE criterion, requiring statistical information in the form of correlation matrices regarding the channel and the additive noise[27]. However, this approach includes the inversion of the correlation matrices, an costly operation to be performed every four OFDM symbols. Several simplifications have been proposed for the MMSE channel estimation problem, including subspace methods [27] and techniques that assume a pre-defined CIR length [28]. Subspace methods exploit the sparsity of the single value decomposition (SVD) of the correlation matrices, which reflects the small number of resolvable propagation paths compared (usually no more than a few tens of paths) to the number of subcarriers (1405, 2809 or 5617 in ISDB-T, depending on the transmission mode). The assumptions behind the subspace methods are clearly more adequate for the SFN channels in question, with large delays between signals coming from different transmitters, and unsurprisingly perform better in these scenarios.

Channel estimation can alternatively follow a least-squares (LS) criterion, which consists on dividing the received pilot signals by the pre-defined pilots, thus obtaining the channel gains at the pilot subcarriers, and then interpolating these gains to obtain the remaining channel gains. The interpolation can be performed via Fourier Transforms [29], which require that a DFT and an IDFT be computed for each interpolation, hence adding considerable complexity to the receiver. This interpolation approach has the additional possibility of exploiting the sparsity of the CIR.

The interpolation can also be performed by passing the channel gains at the pilot subcarriers through interpolating filters. This simpler approach can be implemented via polyphase FIR filters as in [30] or via polynomial filters [31]. Irrespective of the type of filter, it is vital for channels with CIRs spanning the entire cyclic prefix to make sure that the passband comprises the entire CIR and for the stop band to include the images created by the upsampling process. Indeed, the passband of such filters is required to correspond to the size of the cyclic prefix. In our analysis of these interpolators, we found that several polynomial interpolators, such as those proposed in [32] do not fulfill such requirements.

A comprehensive survey of the techniques proposed for channel estimation in OFDM systems can be found in [33].

IV. Results

Some of the solutions proposed in the papers discussed earlier were chosen to be modeled and integrated in an entire ISDB-T receiver for further analysis. This receiver was then implemented in hardware description language and prototyped in FPGA. Tests were performed with this prototype in order to assess its performance in real SFN scenarios. The tests were run in Mode 3 with a cyclic prefix corresponding to $\frac{1}{4}$ of the symbol, and a convolutional coding rate of $\frac{3}{4}$.

In Figure 6, we use a two-tap SFN channel model, with a relative delay δ. For each δ, we plot the lowest attenuation (in dB) of the second tap in relation to the reference tap (set at absolute delay 0) needed for the receiver to be in quasi-error-free (QEF) condition. QEF is defined in [18] as having a bit error rate of 2×10^{-4} after decoding of the convolutional channel code. It is clear from the figure that the receiver is able to achieve QEF for even the most difficult scenario of two equal taps as long as the delay δ corresponds to up to 95% of the size of the cyclic prefix, which in these tests is $252\mu s$ long. Notice that the abrupt change once the delay is longer than the cyclic prefix is coherent with the fact that no algorithms were implemented in this prototype to deal with these cases, and as a result, the ISI is treated as additive noise.

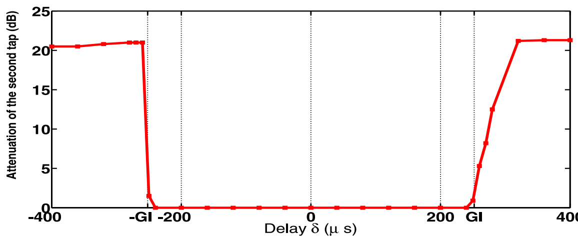

Fig. 6. Attenuation of the second tap as a function of the delay

V. CONCLUSIONS

The deployment of single frequency networks provides significant gains in energy efficiency and coverage area, but at the same time poses numerous challenges to the design of ISDB-T receivers. In this paper, we survey the literature regarding solutions to some of these challenges, and show that the state-of-the-art techniques for symbol timing synchronization are capable of dealing with the issues that arise from the long CIRs generated by SFNs. The results obtained from the prototype corroborate the efficiency of the algorithms discussed here.

VI. ACKNOWLEDGEMENT

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