Some Results on Implementing Low-Complex ICI Cancellation for DVB-H

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Abstract—A combination of receiver windowing and inter-carrier interference (ICI) canceling is proposed for improving the Doppler frequency performance of a DVB-H receiver. The windowing reduces the ICI, and enables ICI cancellation of low complexity to give substantial improvements. Bounds for the possible improvements of ICI cancellation are presented and compared to results from both simulations and measurements on a DVB-H prototype. The found improvements obtained from windowing agree well with that predicted by theory, whereas the gain from ICI cancellation is considerably smaller. This is primarily due to non-ideal channel estimation, which also is discussed. Although the measured performance for ICI cancellation is far from that theoretically possible, the gain in what Doppler frequency can be handled is more than 40%.

Keywords: OFDM, DVB, ICI, ICI Cancellation, Doppler frequency

I. INTRODUCTION

A major technical problem for a system based on Orthogonal Frequency Division Multiplex (OFDM), is its susceptibility to frequency offsets, phase noise, and Doppler frequency in a time-varying channel. This is because inter-carrier interference (ICI) between the OFDM sub-carriers results. The ICI can easily be reduced by increasing the sub-carrier spacing, i.e., making the OFDM symbols shorter. However, because the cyclic prefix (CP) typically used in OFDM systems needs to be long enough to guarantee that no inter-symbol interference (ISI) is experienced, the improved Doppler performance comes at a cost of increased overhead. Especially for broadcast applications where so-called single frequency networks (SFN) are used, the CP must be large.

One system where ICI might be an issue is Digital Video Broadcasting for Handheld Terminals (DVB-H). The physical layer of DVB-H is similar to that of Digital Video Broadcasting - Terrestrial (DVB-T), which originally targeted stationary or low-mobility receivers. Because high-mobility receivers were not addressed, ICI caused by a time-varying channel was not a major concern. To enable better Doppler frequency performance of DVB-H and still not cause the CP to give too much overhead, a 4k mode (an FFT size of 4k) was introduced in addition to the already standardized 2k and 8k modes in DVB-T. However, from broadcast operators point of view, the 8k mode is still the preferred one because of the smaller overhead associated with a larger FFT. In addition, in the US DVB-H will be transmitted at 1.67 GHz and using a bandwidth of only 5 MHz. Because the experienced Doppler frequency is proportional to the carrier frequency, this will be about 2.4 times higher for the system in the US than that experienced at 700 MHz, which is the highest frequency currently proposed for Europe. Furthermore, the reduced bandwidth means that the carrier spacing is reduced accordingly. Effectively, decreasing the bandwidth from 8 MHz to 5 MHz implies that the Doppler frequency needs to be reduced by a factor of 5/8 to keep the ICI power the same. Consequently, DVB-H in the US is roughly four times more sensitive to Doppler frequency than DVB-H in Europe. To compensate for this, the FFT size has to be reduced to 2k or possibly 4k. As will be shown in the next section, ICI cancellation can be expected to be required in case the 4k mode is to be used in the US for high mobility users.

That ICI cancellation is a differentiator when it comes to DVB-H is readily seen in the implementation guidelines of the DVB-H standard [2], where the performance for two kinds of reference receivers is described - A Typical one which does not use ICI cancellation and a Possible one which does use ICI cancellation.

ICI cancellation in relation to DVB has been considered by others, e.g. [6],[13]. The proposed schemes for ICI cancellation are relatively complex compared to the other baseband processing in the receiver because it is based on forming a matrix of coefficients describing the ICI coupling into adjacent channels. The received signal is then multiplied by the inverse of this matrix to remove the ICI.

Another means to reduce the impact of imperfections, like frequency offset, in OFDM systems is by using windowing, as discussed in [9] and [10]. In this paper we show that the gain obtained by using windowing in case of frequency offset or Doppler frequency can be determined by calculating how the leakage between the different sub-carriers is affected by the shape of the applied window.

In addition, a low complexity form of ICI reduction is described. The technique uses an adaptive receiver window to reduce the required number of terms to cancel. Although a smoother window shape is preferred if the ICI level must be considerably reduced, it is demonstrated both analytically.
and by means of measurement on a DVB-H prototype that a very simple window shape might be preferable in case of a low-complexity cancellation approach. The paper is organized as follows. Section II gives the theory, covering how the need for ICI cancellation can be determined, how the impact of windowing can be obtained, and how much ICI cancellation ideally can improve the performance depending on how many of the interfering sub-carriers are canceled. Section III and Section IV present results obtained from simulations and measurements, respectively. Finally, conclusions are given in Section V.

II. THEORY

A. The need for ICI cancellation

ICI cancellation adds by necessity complexity to a receiver implementation. In addition, it is one of the more time consuming parts to develop, test, and verify. Consequently, it is important to determine if ICI cancellation is at all needed. A good starting point is to consider the power level of the ICI caused by a Doppler frequency. Assuming that all the sub-carriers are transmitted at the same average power and that the Doppler spectrum is according to Jakes’ model [7], this is known to be [8]

\[ P_{ICI} = \frac{\pi^2}{6} f_d^2, \]  

(1)

where \( f_d = f_D/\Delta f \) is the normalized Doppler frequency, i.e., the actual Doppler frequency \( f_D \) divided by the sub-carrier spacing \( \Delta f \). The ICI can then be viewed as a noise-floor with a power level given by (1). If the ICI is allowed to reduce the sensitivity of the system by 1 dB, this translates into that the ICI power should be 6 dB below the noise floor. For example, if the system requires a carrier-to-noise-ratio (C/N) of 16 dB, then \( P_{ICI} = -22 \) dB, which means that the normalized Doppler frequency must not exceed 0.062.

Taking DVB-H in Europe as an example, assuming that the carrier frequency is 700 MHz and that the vehicle speed is 90 km/h (25 m/s), the Doppler frequency is \( f_D = 58 \) Hz. In case the 8k mode is used, the sub-carrier spacing is 1.116 kHz, so that \( f_d = 0.052 \), i.e., well below the required 0.062 imposed to not degrade the performance too much.

For the system in the US, on the other hand, the experienced Doppler frequency is \( f_D = 139 \) Hz. In case the 8k mode would be used, the sub-carrier spacing would only be 698 Hz, implying a normalized Doppler of 0.20. Decreasing the FFT size to 4k or 2k will instead give a normalized Doppler frequency of 0.10 and 0.05, respectively. Consequently, if the 2k mode is used there in no need for ICI cancellation, whereas if the 4k mode is utilized, ICI cancellation is required.

B. ICI due to Doppler - Rectangular Windowing

In OFDM, an IFFT is used at the transmitter side and an FFT at the receiver side. The sent sequence is formed by first taking the IFFT, and then pre-appending the last part. The pre-appended part is known as the CP or the guard interval (GI). At the receiver side, an ISI free portion of the transmitted signal is found and then demodulated by an FFT. First, suppose that this is done by using a rectangular window of length \( N \).

This is the standard approach, and henceforth we will refer to this as the case when no windowing is used.

In [5] it was shown that if the channel is assumed to vary in a linear fashion during the OFDM symbol, then the ICI on sub-carrier \( K \) caused by the symbol sent on sub-carrier \( K + L \) is given by

\[ R_{K,K+L} \approx S_{K+L}H'_{K+L} \frac{1}{j2\pi L} = S_{K+L}H'_{K+L}G_L, \]  

(2)

where \( H'_{K+L} \) and \( S_{K+L} \) are the channel change on sub-carrier \( K + L \) during the (information part of the) OFDM symbol and \( S_{K+L} \) is the symbol transmitted on sub-carrier \( K + L \), respectively. Henceforth, we will refer to \( G_L \) as the leakage coefficient. Clearly, it would be desirable to make this as small as possible. A schematic figure for how windowing and ICI cancellation might be implemented is shown in Figure 1.

C. ICI due to Doppler - Non-Rectangular Windowing

In many practical situations, the excess delay of the experienced channel is considerably smaller than the duration of the used GI. One such situation is broadcast, like the newly developed DVB-H standard, where the GI must be chosen for worst case delay spread within the coverage area, but where some users might experience considerably smaller delay spread. If this is the situation, then the part of the GI not affected by ISI might be used to improve the performance of the receiver by applying a non-rectangular window function.

Henceforth, let \( W \) denote the number of samples from the GI that is used in this window. Clearly \( 0 \leq W \leq N_G \). We restrict our attention to windows that preserve the orthogonality between the carriers, i.e., Nyquist windows.

If windowing is used, a part of the GI not affected by ISI is after weighting added to the corresponding part of the information part of the symbol, which also is properly weighted so that a Nyquist window is obtained.

Now, consider using a window function where \( W \) samples from the GI are combined with the corresponding part at the end of the OFDM symbol by multiplying each of these samples by 0.5 and then add them together.
In [5] it was shown that the ICI was given by

\[
R_{K,K+L} = S_{K+L} H'_{K+L} \frac{1}{2 \pi L} \left( 1 + e^{-j \frac{2 \pi}{N} W L} \right)
\]

\[
= S_{K+L} H'_{K+L} \frac{e^{-j \frac{2 \pi}{N} W L}}{2 \pi L} \cos \left( \frac{\pi}{N} W L \right). \quad (3)
\]

The factor \(e^{-j \frac{2 \pi}{N} W L}\) is merely a phase shift caused by how the folding is done. This phase shift can be avoided by having a symmetric window with respect to the FFT position, i.e., by letting the first sample that is fed to the FFT be \(W/2\) samples prior to \(r_0\).

Comparing (2) and (3), it is readily seen that the simple window above reduces the ICI power from the \(L\)th bin by a factor \(\cos^2 \left( \frac{\pi}{N} W L \right)\).

Implementation-wise, the simple window described above is easily implemented because the values of the window are 0, 0.5, and 1, and multiplication with 0.5 is obtained by a one step right shift of the digital value. Below we refer to this window as a 2-step window. Another window function that also is simple to implement is when the window takes the values 0, 0.25, 0.5, 0.75, and 1. Below these windows are referred to as 4-step windows.

In Tables I and II, the leakage coefficients for different sub-carrier offsets, \(L\), and different window lengths are shown for the 2-step windows and the 4-step windows, respectively. The window length is given relative to the FFT size, \(N\). For instance, if the length of the GI is \(N/4\), and \(W = 3N/16\), then 75% of the GI is used for the window. The first row \((W = 0)\) corresponds to that a rectangular window is used. As can be seen, the leakage coefficients are reduced, especially as \(L\) is increased.

D. Bounds on the Achievable Performance Gains

If the statistics in terms of the sent data and the channel variations are the same for all sub-carriers, the average power of the ICI can be written (compare (2))

\[
P_{ICI} \sim f_e^2 \sum_{L \neq 0} |G_L|^2. \quad (4)
\]

With ICI cancellation, the total power is calculated by removing the corresponding terms from (4). The results are presented in Tables III and IV for 2-step windows and 4-step windows, respectively. Canceling 2 bins means that ICI from the two closest bins (one on each side, i.e., \(L = \pm 1\)) are canceled, and canceling 4 bins means that ICI from the four closest bins (two on each side, i.e., \(L = \pm 1, \pm 2\)) are canceled, etc.

Because the ICI is proportional to \(f_e^2\), see (4), the corresponding increase in what Doppler frequency can be handled is easily obtained. For instance, with \(W = 3N/16\) and no canceling \(f_e\) can be increased by about 35 %, and in case the ICI from the two closest carriers is perfectly canceled, then the maximum Doppler frequency would be improved by almost a factor of three.

E. ICI due to Frequency error

Frequency offset can be viewed as a special case of a varying channel, where the variation is a phase shift. Let \(f_e\) denote the normalized frequency error, i.e., the frequency error divided by the carrier spacing. It is then well-known, e.g. [8] and [12], that the ICI power is given by

\[
P_{ICI} = \frac{\pi^2}{3} f_e^2. \quad (5)
\]

Deriving (5) is straightforward using (2) and the approximation that for a frequency offset \(H' = \exp(j2\pi f_e) \simeq 1 + j2\pi f_e\) for small frequency errors. Because the only difference between ICI caused by Doppler frequency and ICI caused by a frequency error is a scale factor, it follows that the gains (in dB) obtained by using non-rectangular windowing and ICI cancellation are the same for frequency offset.

III. SIMULATION RESULTS

As seen from (2), successful ICI cancellation requires that the channel as well as its derivative can be estimated sufficiently well. To evaluate how well this requirement can
be met in an actual system, simulations were performed for the 8k mode in DVB-H, [1], [4] when the largest GI interval was used. This means that the carrier spacing is \( \Delta f = 1116 \) Hz. All simulations are performed using the TU6 channel, [2], [11].

Furthermore, if the channel estimation is performed by first interpolating in the time direction, the Nyquist rate equals 112 Hz (normalized Doppler \( f_d = 0.1 \)). To enable higher Doppler frequencies, the channel estimation was therefore done by interpolation in the frequency direction directly, exploiting that the delay spread of the TU6 channel is sufficiently small to allow for this.

The forward error correction (FEC) coding used in DVB-H consists of the concatenated coding scheme used in DVB-T [3] extended with another layer of coding on the link layer, denoted MPE-FEC, which gives time-diversity of some 200 ms under typical operating conditions. To evaluate the gain that can be obtained by windowing and ICI cancellation, the byte error rate at the output of the concatenated code was used. The operating point where the MPE-FEC in DVB-H will give satisfactory reception depends of course on the statistics of the errors out from the concatenated code as well as on the code rate used by the MPE-FEC. Moreover, it depends on what approach is taken for the decoding of the MPE-FEC.

In [2], it is suggested to use erasure decoding. That is, the MPE and MPE-FEC sections that contain errors after decoding the concatenated code are marked as unreliable, and then the MPE-FEC uses erasure decoding. We found, however, that better performance was obtained if the MPE-FEC instead uses error correction. The reason being that a vast majority of the symbols that are declared as unreliable are in fact correct. If the errors at the output of the concatenated code are assumed to be spread uniformly over the MPE-FEC frame, the MPE-FEC frame size is 2 Mbit, and the rate of the MPE-FEC is \( 3/4 \), this means that a MPE-FEC frame is decoded correctly if none of the rows contains more than 32 errors. A typical value used within the DVB-H standardization for the required performance is a frame error rate of 5 % (MFER = 5%). To achieve MFER = 5%, it is easily found that a symbol error rate (SER) of 6.1 % after the concatenated code is required. In the figures, this is marked with a horizontal line. It can be noted that the relative gain obtained by using windowing and ICI cancellation is not sensitive to the exact choice of operating point, so even if the requirements on the SER would be slightly different the gain would be about the same.

All simulations are performed for 16-QAM and rate 1/2 of the convolutional code (the inner code of the above mentioned concatenated code). Also, in all simulations where ICI canceling is applied, only the ICI from the two adjacent bins are canceled, i.e., \( L = \pm 1 \). The simulations are performed at large \( C/N \), so errors are due to channel estimation and/or ICI caused by Doppler.

In Figure 2, the performance is shown when windowing is used, but no ICI cancellation. The window length is 1536 samples, i.e., \( W = 3/16 \). Considering the 2-step window, it is seen that the allowed Doppler frequency is increased from 180 Hz to 235 Hz. This corresponds to an improvement of 30%, which means that the window effectively has reduced the leakage coefficient by 2.3 dB. Referring to Table III, the predicted gain was 2.65 dB or an increase in Doppler frequency by 36 %. It can also be seen that the "smoother" windows perform worse, which also can be expected by comparing the results in tables III and IV in case of no cancellation.

The simulated performance of ICI cancellation is shown in Figure 3. As can be seen, the 2-step window gives the best result also in this case. The allowed Doppler frequency has been increased to 260 Hz, or 44 %, which equals 3.2 dB, which is far from the 9.12 dB that ideally would have been the improvement with ideal cancellation. This can partly be explained by estimation errors, in particular for the channel derivative, but also to the simplified scheme for ICI cancellation.

IV. IMPLEMENTATION AND MEASUREMENT RESULTS

The proposed ICI cancellation was implemented in an Field Programmable Gate Array (FPGA) and tested both with
frequency errors and a time-varying channel. When the work with the ICI cancellation started, there was already a working DVB-H prototype implemented in the FPGA, so the ICI cancellation unit was implemented as to fit in as smoothly as possible within this implementation. In the design, focus was on functionality and little attention was paid to things as power consumption and gate count, which would have been the case if a real product would have been targeted.

The Doppler frequency performance was measured in a similar way as is used in [2], i.e., the required $C/N$ is plotted versus the Doppler frequency. If it is assumed that ICI and noise have similar effect on the performance, we might define the effective $C/N$ as

$$\left(\frac{C}{N}\right)_{eff} = \frac{C}{N + P_{ICI}}. \quad (6)$$

As the Doppler frequency is increased, so is $P_{ICI}$, and as a consequence $C/N$ must be increased in order for $(C/N)_{eff}$ to be kept constant. All measurements are performed with the TU6 channel, and channel estimation is performed by directly interpolating in the frequency direction.

Figure 4 shows the performance without ICI cancellation and a 2-step window. The Doppler frequency is in case of a 1024 samples long window ($N/8$) increased from 145 Hz to 180 Hz at a required $C/N$ of 25 dB. (The 25 dB value is chosen somewhat arbitrary to allow for an estimation of the gain in Doppler frequency performance.) This corresponds to a gain of 1.87 dB, which agrees well with the 1.73 dB predicted by Table III. As can be see in Figure 4, also a very short window of length $N/32$ gives some gain.

Finally, performance for ICI cancellation is presented in Figure 5. If a 2-step window of length $N/8$ and ICI cancellation is applied, then the Doppler frequency can be increased to about 210 Hz at a required $C/N$ of 25 dB, or a total gain of 45 %, which is slightly larger than the simulation results keeping in mind that the simulations were performed with a window of length $3N/16$.

V. CONCLUSION

The gain by using windowing and ICI cancellation for DVB-H was in this paper derived analytically and compared to both simulations and measurement results. Good agreement between theory and measured performance was seen for windowing, whereas there was a large difference concerning ICI cancellation. This can be attributed to the ICI cancellation requires good estimates of both the transmitted signal and the channel variation in order to work ideally. Still, the measurements indicate that the Doppler performance can be increased by more than 40 % for a DVB-H system.

REFERENCES