A Channel Characterization Technique Using Frequency Domain Pilot Time Domain Correlation Method for DVB-T Systems

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Abstract* —A new channel characterization technique using frequency-domain pilot time-domain correlation (FPTC) method for DVB-T systems is proposed in this paper. The proposed technique is based on the time-domain correlation between the received signal and the pilot sequence embedded in the DVB-T signal, which is derived from the frequency domain pilots and known to the receiver. Interruption to the broadcasting service can be avoided, since only regular DVB-T signal is needed for channel characterization. In comparison with other Digital TV characterization techniques, the major advantages of this proposal is its implementation simplicity, large dynamic range, and the robustness against synchronization errors. Channel impulse responses can be accurately estimated without timing recovery. The impact of the non-perfect carrier recovery is very small, since the correlation is only computed on a short time period of the received signal. The proposed method has been verified through numerical simulations and lab tests. Possible ways of improving the estimation accuracy are also discussed*[1].

***Index Terms*—Channel characterization, orthogonal frequency division multiplexing (OFDM), DVB-T, synchronization.**

I. INTRODUCTION

ORTHOGONAL Frequency Division Multiplexing (OFDM) has recently been applied widely in wireless communication systems due to its high data rate transmission capability with high bandwidth efficiency and its robustness to multipath distortion. It was first standardized for Digital Audio and Video Broadcasting applications in Europe, and later for digital subscriber loops (DSL) and wireless LAN. During the deployment of terrestrial DTV broadcasting systems, very often the channel characteristics have to be captured for the DTV coverage study, reception problem diagnosis and service planning. DTV channel characterization can generally be divided into two categories: in-service channel characterization and out-of-service channel characterization. In the first case, channel characterization for DVB-T system is realized through the demodulation of the DTV signal. In this respect, channel characterization is obtained through channel estimation, which is usually realized by demodulation of pilots. Pilots are either inserted into all of the subcarriers of transmitted OFDM symbols with a specific period or inserted into some subcarriers for each OFDM symbol. Channel characterization, or estimation, can then be realized through the demodulation of the OFDM signal in the frequency domain. However, channel conditions are often very poor and reception of the DTV program may not be possible when channel characteristics are needed for poor service diagnosis. The dynamic range and time-domain resolution of the channel estimation obtained this way is then limited. Also, the reliability of the system synchronization for the DVB-T receiver is also a problem. Synchronization error can be significant, under severe multipath conditions or strong co-channel and adjacent channel interference. For out-of-service channel characterization, the regular broadcasting program has to be interrupted. The transmission and reception may use specially tailored test signals. These test signals must occupy the same spectrum and have the same average power as a DTV signal. Therefore, a new in-service DTV channel characterization which is robust to strong interference and synchronization errors is desirable.

To solve the problem, a simple in-service channel characterization technique using a frequency-domain pilot time-domain correlation (FPTC) method for DVB-T system is proposed in this paper. This new technique is based on the time domain correlation between the received signal and the time domain pilot sequence embedded in the OFDM signal, which is derived from the frequency domain pilots and known to the channel estimation device. It is shown that the time domain correlation function of the received signal and the pilot sequence can be approximated as the convolution between the channel impulse response and the time domain autocorrelation function of the pilot sequence. Channel impulse response is therefore obtained, since the autocorrelation function of the pilot sequence is also known at the receiver. Initial channel estimation can be greatly simplified if the number of pilot tones is large enough such that the autocorrelation function of the pilot sequence can be approximated as a Kronecker delta function. Under this condition, the channel impulse response can be directly estimated through the correlation computation. When the autocorrelation function of the pilot sequence is not

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a perfect delta impulse function due to the bandlimitation effect, the impact of non-ideal autocorrelation function has to be removed for an accurate channel estimation through some deconvolution process. As an example, the time domain pilot sequence is generated from scattered pilot described in the DVB-T standard. The proposed technique is verified through numerical simulations and field tests. Compared with other channel characterization techniques, the major advantages of the proposed estimation method is its implementation simplicity and robustness to synchronization and frequency offsets. Channel impulse response can be estimated without timing recovery. The impact of the non-perfect carrier recovery is negligible since the correlation is only computed over a short time period of the received signal.

The organization of this paper is as follows: a brief review of the in-service channel characterization for DVB-T system is given in Section II. The principle of the proposed FPTC is discussed in Section III. In Section IV, characteristics of the DVB-T pilot sequence and the corresponding autocorrelation function is studied. Simulation results to validate the estimation method are presented in Section V. Possible ways of improving the estimation accuracy will also be discussed.

II. IN SERVICE CHANNEL CHARACTERIZATION FOR DVB-T SYSTEMS

When the DVB-T signal is employed, in-service channel characterization is equivalent to channel estimation. As we mentioned earlier, in-service channel characterization for a DVB-T system is based on demodulation of the OFDM pilots in the frequency domain. Two kinds of OFDM pilots are often used, i.e., block-type and comb-type pilots. The first case, i.e. block-type pilot channel estimation, has been developed under the assumption of slow varying channel conditions. The second, the comb-type pilot channel estimation, has been introduced to meet the need when the channel changes even from one OFDM symbol to the subsequent one. The comb-type pilot channel estimation consists of algorithms to estimate the channel at pilot frequencies and interpolate the channel. For both cases, the initial channel estimation is achieved in the frequency domain by demodulating the OFDM symbol and comparing the pilot signal before and after transmission. Frequency domain channel estimation for OFDM system is usually based on the demodulation of pilot subcarriers [1]-[2]. Incoming binary data at the OFDM transmitter side is first grouped and mapped according to the modulation scheme. Without loss of generality, denote the symbol to be transmitted for the k-th subcarrier as X_k. Comb or block pilots are inserted for channel estimation purposes at the transmitter side before the parallel data X_k, of length of N, into the serial time domain signal $x(n)$ with N samples.

The guard interval, or cyclic prefix, chosen longer than the expected channel delay spread, is inserted to eliminate inter-symbol interference (ISI) and inter-carrier interference (ICI) before transmission [3]. The transmitted signal $x(n)$ passes through the frequency selective time varying fading channel with additive noise. The channel impulse response is given by:

$$h(n) = \sum_{n=0}^{L-1} h_n \delta\left(t - \tau_n\right) \tag{1}$$

where L, h_n, and τ_n are the total number of paths, and complex gains and delays for the n-th path, respectively. At the receiver, after passing to discrete domain through A/D and low pass filtering, the guard interval is removed and $y(n)$ is sent to the DFT block:

$$Y_k = DFT\left\{y(n)\right\} = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} y_n e^{-j\frac{2\pi nk}{N}} \tag{2}$$

When the duration of the channel impulse response is shorter than the guard interval, then there is no intersymbol interference. Assuming also that there is no synchronization error, the relationship between Y_k, X_k and the channel transfer function H_k can be formulated as:

$$Y_k = H_k X_k + W_k \tag{3}$$

where W_k is the Gaussian noise for the k-th subcarrier after DFT demodulation. For the pilot subcarriers, the transmitted information X_k is known to the receiver. Therefore, the frequency response of the channel at pilot frequencies can be estimated simply using:

$$\hat{H}_k = \frac{Y_k}{X_k} - \frac{W_k}{X_k} = \frac{Y_k}{X_k} - W_k^{'} \tag{4}$$

Channel estimation in (4) is based on the Least Square (LS) model. A more elaborate method that is capable of reducing the effect of $W_k^{'}$ is linear minimum mean-square error (LMMSE) [4,5]. However, the computational complexity for LMMSE is significant as a matrix inversion is involved, especially when the total number of the subcarriers is large, as is the case in the DVB-T systems: the 2k DVB-T system uses 1705 subcarriers while the 8k version employs 6817 subcarriers.

Another very important assumption for the above frequency domain channel estimation is the perfect synchronization. It is well known that an OFDM system is very sensitive to frequency offsets. Under severe multipath distortion and strong interference, synchronization error of the OFDM receiver can severely degrade the frequency domain channel estimation. There are two types of synchronization errors: timing and frequency offsets. Timing offset will rotate all the DFT outputs. However, with the frequency pilots, timing offset can be easily estimated and compensated for. However, frequency offset will affect the orthogonality among the subcarriers and thus lead to inter-carrier interference (ICI). Denoting Δk as the relative normalized frequency offset (the ratio of the actual

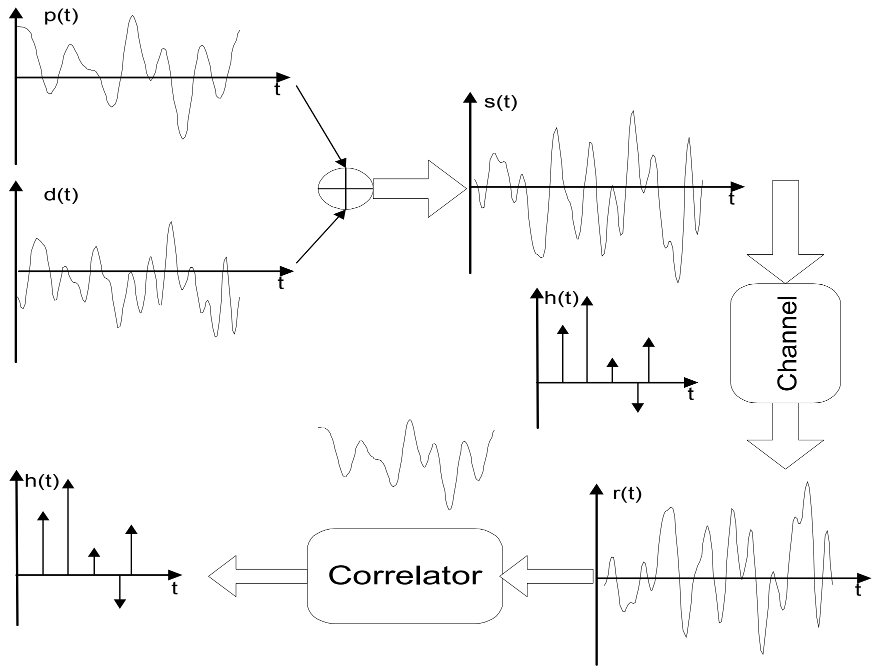

Fig. 1. Principle of the proposed frequency pilot time domain correlation technique.

frequency offset to the sub-carrier spacing), equation (3) now becomes [8]:

$$Y_k = X_k H_k \left\{ \frac{\sin(\pi \Delta k)}{N \sin(\pi \Delta k / N)} \right\} \cdot e^{j\pi \Delta k (N-1)/N} + I_k + W_k \quad (5)$$

where I_k denotes the inter-carrier interference (ICI), caused by the frequency offset:

$$I_k = \sum_{\substack{l=-K \\ l \neq k}}^{K} X_l H_l \left\{ \frac{\sin[\pi \Delta k]}{N \sin[\pi(l-k+\Delta k)/N]} \right\} \times e^{j\pi(N-1)(l-k+\Delta k)/N} \quad (6)$$

Using (4) for channel estimation can cause very significant errors with only modest synchronization offsets. Therefore, a new channel estimation method with more robustness to synchronization impairments, particularly frequency offsets, is desired.

In [6,7], a frequency pilot time average (FPTA) method is proposed. In the FPTA approach, positive and negative alternatively polarized pilot tones are multiplexed with data at a pilot ratio of *1/K*. Since there are *K* identical parts of time-domain pilot samples within one OFDM symbol, the corresponding parts of the received samples are averaged over the *K* parts in the time domain. Channel estimation in FPTA is realized through the demodulation of the averaged pilot sequence, and therefore, the performance with synchronization error is identical to that of the channel estimator in (4) [7].

It is noted here that the pilot assignment in FPTA leads to a non-zero DC offset in the OFDM signal, which has to be avoided in any commercial communication system. FPTA is based on the assumption that there are *K* identical parts of the pilot sequence within one OFDM symbol. However, as we will show in the next section, this assumption is only valid when all the subcarriers in the OFDM system are used. However, this is often impractical for communication system designs. As stated before, only 1705 subcarriers are used for DVB-T system in its 2k mode because filter design is simplified with this arrangement.

The proposed frequency-domain pilot time-domain correlation (FPTC) channel characterization method for OFDM system is based on the time domain correlation between the received signal and the time domain pilot sequence embedded in the OFDM signal, which is derived from the frequency domain pilots and known to the receiver. The principle of the technique is demonstrated in the next section. The major advantage of this new channel estimation technique is its robustness to strong interference and frequency offset. Interruption of the broadcasting service is also avoided.

III. PRINCIPLES OF THE PROPOSED FPTC TECHNIQUE

The principle of the proposed time domain channel estimation is shown in Figure 1. An OFDM symbol is given by the *N*-point complex modulation sequence:

$$s(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k e^{j\frac{2\pi nk}{N}} \qquad n=0,\ 1,\ 2,\ \ldots\ldots,\ N-1 \quad (7)$$

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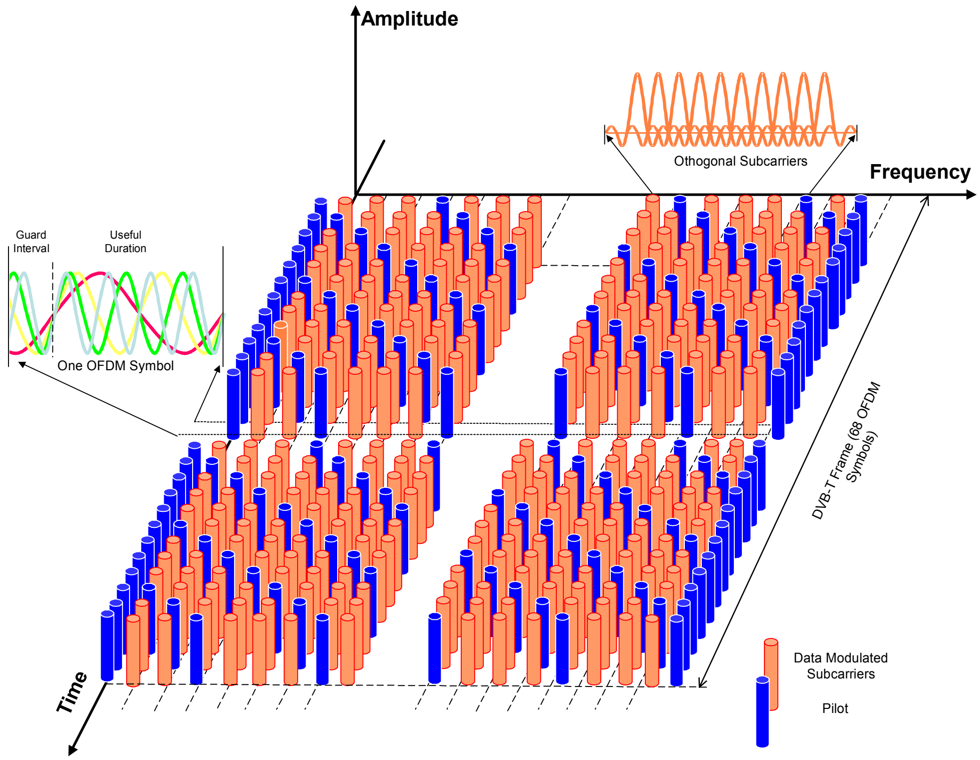

Fig. 2. DVB-T frame structure (only scattered pilots are plotted).

It consists of N complex sinusoids or subcarriers modulated with the complex data X_k, which can be divided into two different sets, i.e., the data symbol to be transmitted and the pilot symbols for channel synchronization and estimation. Denote the subcarrier sets for these two symbol sets as D and P, respectively. Eq. (7) can be re-organized as:

$$s(n) = d(n) + p(n) \tag{8}$$

where

$$d(n) = \frac{1}{\sqrt{N}} \sum_{k \in D} X_k e^{j\frac{2\pi nk}{N}} \tag{9}$$

and

$$p(n) = \frac{1}{\sqrt{N}} \sum_{k \in P} X_k e^{j\frac{2\pi nk}{N}} \tag{10}$$

After passing through a multipath channel characterized by its complex impulse response *h(n)*, the received signal *r(n)* can be written as

$$r(n) = d(n) \otimes h(n) + p(n) \otimes h(n) + w(n) \tag{11}$$

The correlation function between the received signal *r(n)* and the time domain pilot sequence $p(n)$ is given by

$$R_{rp} = R_{pp} \otimes h(n) + R_{dp} \otimes h(n) + w(n) \otimes h(n) \tag{12}$$

where R_{xy} denotes the crosscorrelation between signal x and y. Using the central limit theorem (with a sufficiently large N), R_{dp} can be approximated as a Gaussian distributed variable with mean zero and variance of $\frac{\sigma_d^2 \sigma_p^2}{N}$. Similarly, the autocorrelation function of $p(n)$ can be formulated as

$$R_{pp}(m) = \frac{1}{N} \sum_{\substack{n=0 \\ n \in P}}^{N-1} p(n) p^*(n-m)$$
$$= \begin{cases} \frac{1}{N} \sum_{\substack{n=0 \\ n \in P}}^{N-1} p(n) p^*(n) \approx \sigma_p^2 & , m = 0 \\ w(m) & , m \neq 0 \end{cases} \tag{13}$$

where *w(m)* is a Gaussian noise with variance of $\frac{\sigma_p^4}{N}$. Note that the convolution of a Gaussian noise with *h(n)* is still Gaussian distributed. For a simple channel estimation, R_{rp} usually is truncated to R'_{rp} such that significant part of the

Continual indices for continual pilot carriers	
2k mode	8k mode
0 48 54 87 141 156 192 201 255 279 282 333 432 450 483 525 531 618 636 714 759 765 780 804 873 888 918 939 942 969 984 1050 1101 1107 1110 1137 1140 1146 1206 1269 1323 1377 1491 1683 1704	0 48 54 87 141 156 192 201 255 279 282 333 432 450 483 525 531 618 636 714 759 765 780 804 873 888 918 939 942 969 984 1050 1101 1107 1110 1137 1140 1146 1206 1269 1323 1377 1491 1683 1704 1752 1758 1791 1845 1860 1896 1905 1959 1983 1986 2037 2136 2154 2187 2229 2235 2322 2340 2418 2463 2469 2484 2508 2577 2592 2622 2643 2646 2673 2688 2754 2805 2811 2814 2841 2844 2850 2910 2973 3027 3081 3195 3387 3408 3456 3462 3495 3549 3564 3600 3609 3663 3687 3690 3741 3840 3858 3891 3933 3939 4026 4044 4122 4167 4173 4188 4212 4281 4296 4326 4347 4350 4377 4392 4458 4509 4515 4518 4545 4548 4554 4614 4677 4731 4785 4899 5091 5112 5160 5166 5199 5253 5268 5304 5313 5367 5391 5394 5445 5544 5562 5595 5637 5643 5730 5748 5826 5871 5877 5892 5916 5985 6000 6030 6051 6054 6081 6096 6162 6213 6219 6222 6249 6252 6258 6318 6381 6435 6489 6603 6795 6816

Table 1. Carrier indices for DVB-T continual pilot carriers.

energy is included in R'_{rp}. For the convenience of the analysis, we assume R'_{rp} has the same duration as *h(n)*

$$R'_{rp}(n) \approx w_1(n) + h(n)\sigma_p^2 \tag{14}$$

where $w_1(n)$ is the combined interference from the first item in (11) and *w(m)* in (13). The channel estimation normalized to the main path can be therefore obtained through the correlation between the received signal and the time domain pilot sequence as

$$\hat{h}(n) = \frac{R'_{rp}(n)}{R'_{rp\_\max}} = \frac{R'_{rp}(n)}{h_{\max}\sigma_p^2} + w_2(n) \tag{15}$$

where the subscript *max* denotes the index of the main path and $w_2(n)$ is the interference term from $w_1(n)$.

IV. AUTO-CORRELATION OF THE DVB-T PILOT SEQUENCE

The principle of the FPTC technique was discussed in the previous section. To demonstrate the FPTC principle, the autocorrelation function of the pilot sequence has been simplified as a Kronecker function. However, in a practical OFDM system like DVB-T, the autocorrelation function of the pilot sequence is always affected by the selection of the pilots, i.e., the auto-correlation is not ideally shaped.

Two types of pilots are used in DVB-T system, i.e., scattered pilots and continual pilots. For the symbol index *l* (ranging from 0 to 67), subcarriers for whose index *k* belongs to the subset

$$k = k_{\min} + 3\times(l \bmod 4) + 12p, \qquad k \in [k_{\min},\, k_{\max}] \tag{16}$$

where *p* is an integer not less than zero. It is clear that for a given DVB-T symbol, i.e. with a fixed *l*, all the scattered pilots are evenly distributed with a spacing of 12 subcarriers. However, the initial position of the scattered pilots will be shifted, as this can be observed in Figure 2. Another fact is that the ratio between the scattered pilots and the rest of the subcarriers is one to 12. This is important in determining the signal to noise ratio of the correlation function.

Subcarriers with the indices shown in Table 1 are continual pilots, i.e., these subcarriers will be always used as pilots by all OFDM symbols. There are 177 continual pilots in the 8k mode and 45 in the 2k mode.

A. Periodicity of the scattered pilot sequence

Since the total number of the scattered pilots are much larger than the available continual pilots, it is important to study the pilot sequence generated from scattered pilots. This pilot sequence may possess periodic property due to the insertion pattern of the scattered pilots.

Let us re-examine the equation (10) and consider only the scattered pilots:

$$p(n) = \frac{1}{\sqrt{N}} \sum_{\substack{k=0 \\ k\in P}}^{N-1} X_k e^{j\frac{2\pi nk}{N}}$$

$$n=0,\ 1,\ 2,\ \ldots\ldots,\ N-1 \tag{17}$$

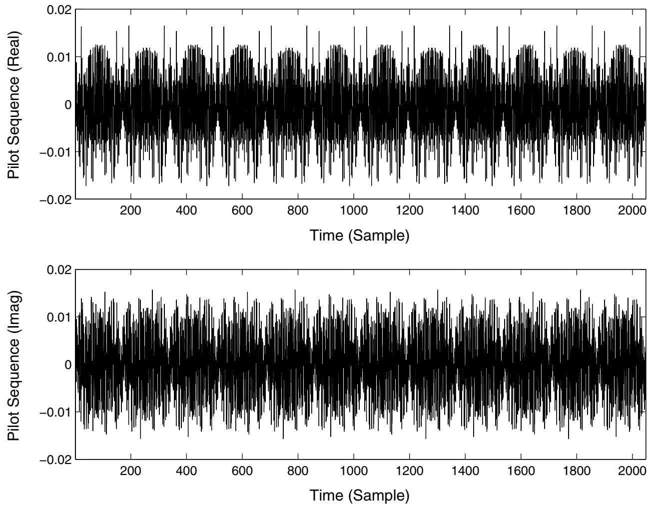

Fig. 3. Pilot Sequence of an OFDM system with 2048 subcarriers. The ratio between the number of data subcarriers and the pilots is 12.

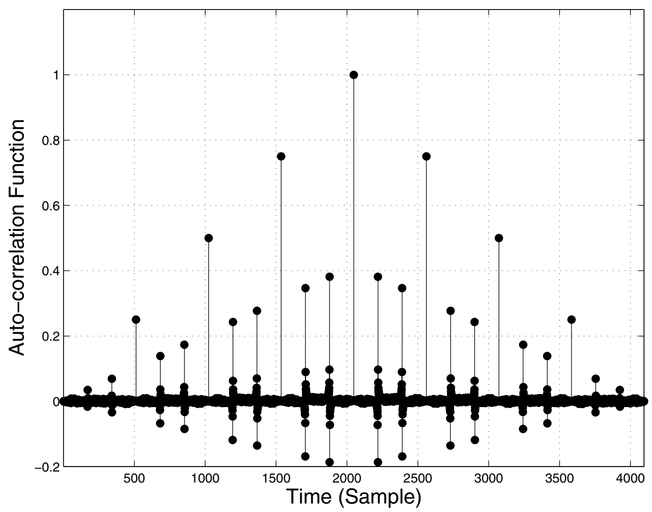

Fig. 4a. Autocorrelation function of the pilot sequence of Fig. 3.

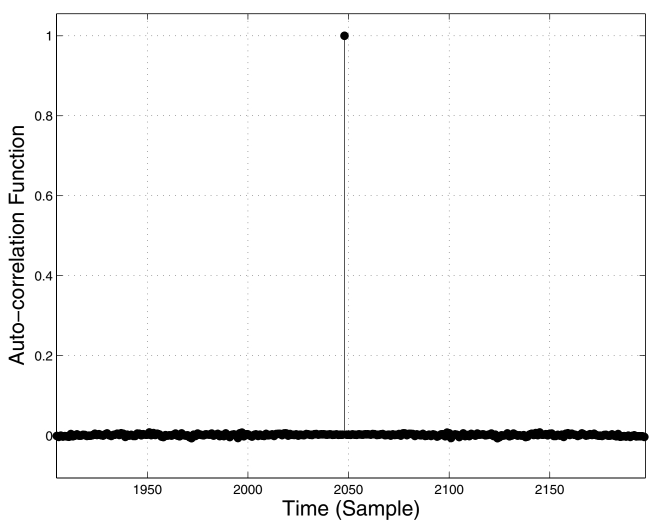

Fig. 4b. Main peak (enlargement) of the autocorrelation function seen in Fig. 4a.

Assume that all the subcarriers of the OFDM system are used and all the pilots are inserted with a certain pattern, e.g., evenly multiplexed with the data subcarriers. This arrangement permits the simple implementation of the frequency interpolation after the initial channel estimation. Denote the index of the first pilot as k_1, the normalized pilot spacing as Δp, and the total number of pilot subcarriers as *M.* The relationship between Δp and M is:

$$M \cdot \Delta p = N \tag{18}$$

Eq. (17) can be re-arranged as:

$$\begin{aligned} p(n) &= \frac{1}{\sqrt{N}} \sum_{k'=0}^{M-1} X_{k'} e^{j\frac{2\pi n(k_1+\Delta p k')}{N}} \\ &= \frac{1}{\sqrt{N}} e^{j\frac{2\pi n k_1}{N}} \left(\sum_{k'=0}^{M-1} X_{k'} e^{j\frac{2\pi n \Delta p k'}{N}} \right) \\ &= \frac{1}{\sqrt{N}} e^{j\frac{2\pi n k_1}{N}} \left(\sum_{k'=0}^{M-1} X_{k'} e^{j\frac{2\pi n k'}{M}} \right) \end{aligned} \tag{19}$$

The item in brackets in the above equation is an M points IFFT. Since the pilot sequence has N samples in the time domain, it can be expected that the item within the bracket is a periodical signal with Δp cycles within the duration of one OFDM symbol. The entire pilot sequence will be the periodical signal in the brackets, modulated by the first pilot tone. Eq. (19) suggests that the assumption of the K identical pilot sequences in FPTA [6,7] is invalid when all the subcarriers are not used by an OFDM system. For continual pilots of the DVB-T system, since their indices are randomly selected, as shown in Table 1, there is no periodical property for the pilot sequence generated from the continual pilots. Pilot sequence of an OFDM system with 2048 subcarriers and the corresponding autocorrelation function are shown in Figs. 3 and 4, respectively. The ratio between the number of data subcarriers and the pilots is 12. The modulation schemes for data carriers and pilots are described in the DVB-T standard [9]. Note that in Figs. 3 and 4, all 2048 carriers are used.

B. Bandlimitation effect

As mentioned before, not all the subcarriers are used in a practical OFDM system. For example, in the DVB-T 2k mode, only 1705 of the 2048 subcarriers are used. The reduction in the number of subcarriers is done mainly to simplify the filter design. This is equivalent to applying a rectangular window in the frequency domain with a width of 1705 subcarriers, to the X_k in (7) before the IDFT modulation. Therefore, a sinc function shaped main lobe in the autocorrelation is expected due to the bandlimitation effect. This can be verified through Figs. 5 and 6. The periodicity of the pilot sequence in Fig. 5 also becomes less obvious because of the bandlimitation effect.

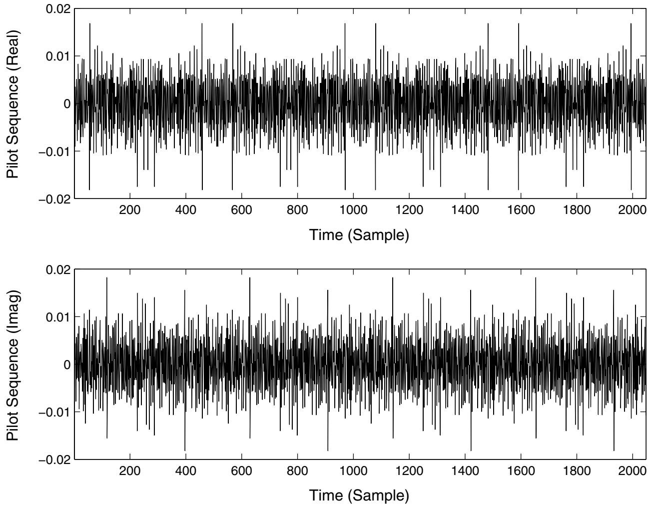

Fig. 5. Pilot sequence of a 2K mode DVB-T system with 1705 subcarriers. The ratio between the number of data subcarriers and the scattered pilots is 12.

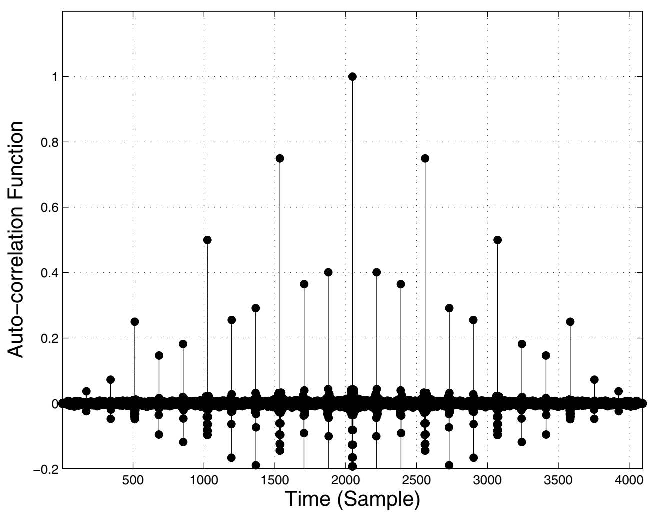

Fig. 6a. Autocorrelation function of the pilot sequence of Fig. 5.

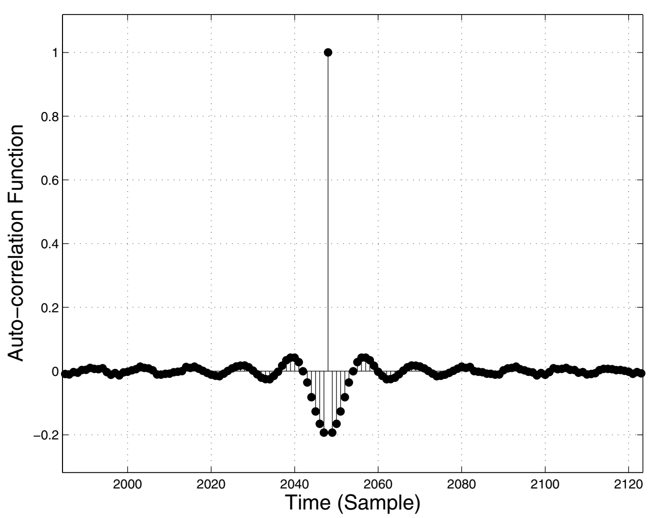

Fig 6b. Main peak of the autocorrelation function in Fig. 6a.

V. Numerical Results

The proposed OFDM channel estimation technique using frequency pilot time domain correlation is evaluated through numerical simulations. Parameters for the DVB-T can be found in the DVB-T standard [9]. The DVB-T 2k mode was used for all the simulations.

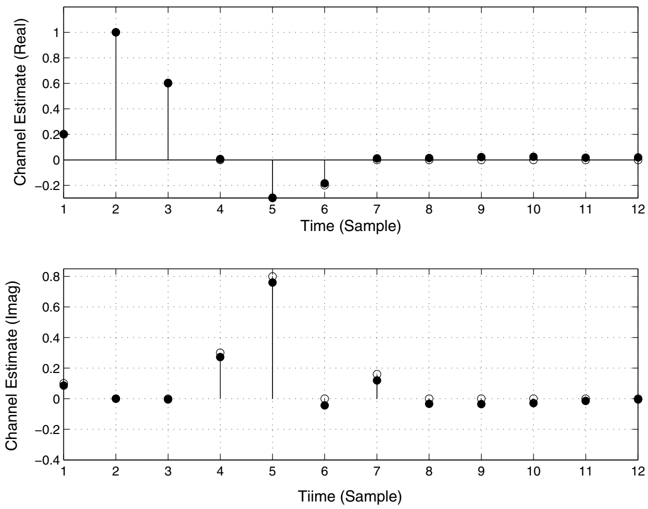

Fig .7a. Estimated complex impulse response using FPTC with a relative frequency offset of 0.04.

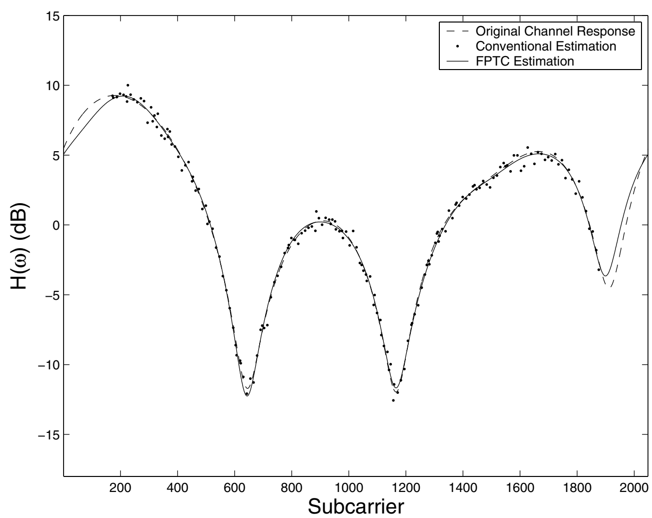

Fig.7b. Comparison between the estimated channel frequency response from the conventional domain channel estimator and the FPTC with a relative frequency offset of 0.04.

Pilot sequences with data to pilot ratio of 12 and the corresponding autocorrelation function were shown in Figs. 3 and 4. In Fig. 3, all 2048 subcarriers are used to generate the pilot sequence. Ideal autocorrelation peak can be observed in Fig. 4b. Therefore, 12 identical parts can be seen in the pilot sequence. When only 1705 subcarriers are used according to the DVB-T standard, the periodical property of the pilot sequence becomes much less obvious as depicted in Fig. 5, due to the modulation by the first subcarrier indicated in (19). The bandlimited pilot sequence and its autocorrelation function are shown in Figs. 5, and 6 respectively. Due to the bandlimitation effect, a sinc shaped autocorrelation is observed. Figs. 5 and 6 also indicate that the proposed channel estimation technique can be used to estimate only channels having delay spreads less than 1/12 of the OFDM symbol duration, which is nevertheless sufficient for most of Digital TV broadcast applications. Further signal processing can be used to increase the estimation interval for the channel impulse response when only some part of the pilot sequence is used for channel estimation.

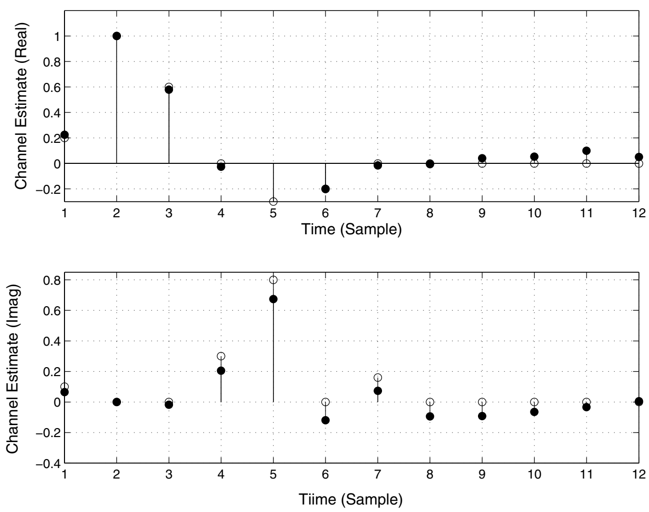

Fig. 8a. Estimated impulse response using FPTC with a relative normalized frequency offset of 0.24.

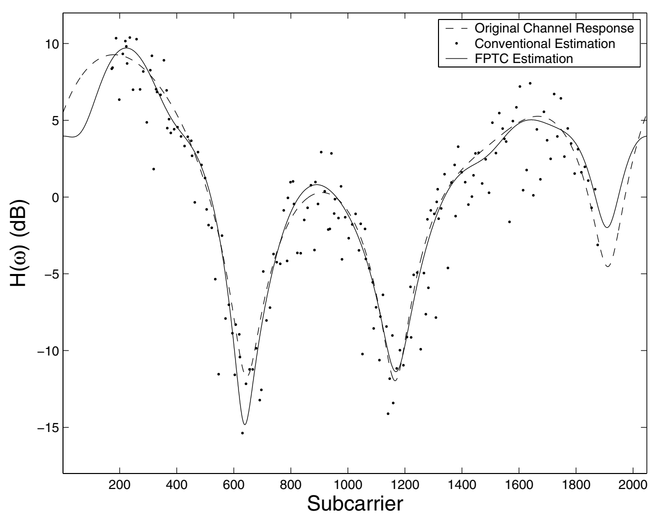

Fig.8b. Comparison between the estimated channel frequency response from conventional domain channel estimator and the FPTC with a relative normalized frequency offset of 0.24.

To simulate the channel estimation process, a complex multipath channel is used in the simulation. The crosscorrelation function between the received signal and the known pilot sequence was computed. A deconvolution algorithm was also used to remove the non-ideal shape of the autocorrelation function shown in Fig 6. A determined frequency offset was then added to evaluate the channel estimation robustness to synchronization errors. When a relative frequency offset of 0.04 was used, the performance of the FPTC is slightly better than the conventional frequency domain channel estimation using the DFT demodulation of the OFDM signal. However, when the frequency offset is increased, the advantage of the FPTC is more obvious, as indicated by the estimated frequency channel response shown in Fig. 8(b) with a normalized frequency offset of 0.24. The proposed FPTC technique is significantly robust to frequency offset as conventional OFDM receiver can only tolerate around three percent of normalized frequency offset.

VI. CONCLUSION

A new channel characterization technique using frequency-domain pilot time-domain correlation (FPTC) method for the DVB-T system is presented. The proposed technique is based on the time-domain correlation between the received signal and the pilot sequence embedded in the DVB-T signal. The characteristics of the DVB-T pilot sequence are studied. In particular, the periodicity and bandlimitation effects are analyzed. The impact of the frequency offset on the proposed FPTC is evaluated through Monte Carlo simulations. Compared with other channel estimation techniques, the major advantage of this proposal is its simple implementation and robustness to synchronization errors. Channel impulse responses can be estimated without timing recovery. The impact of the non-perfect carrier recovery is very small since the correlation is only computed on a short period of the received signal. The proposed method has been verified through numerical simulations. Possible ways of improving the estimation accuracy were also discussed.

REFERENCES

[1] M.-X. Chang and Y. T. Su, “Model-Based Channel Estimation for OFDM Signals in Rayleigh Fading,” *IEEE Trans. Communications*, vol. 50, no.4, pp. 540-544, April, 2002.

[2] Y. Li, "Simplified Channel Estimation for OFDM Systems with Multiple Transmit Antennas*", IEEE Trans. on Wireless Communications*, Vol. 1, no.1, pp 67-75, Jan. 2002.

[3] J.A.C. Bingham, "Multicarrier modulation for data transmission: An ideal whose time has come", *IEEE Commun. Mag.,* vol. 28, no. 5, pp. 5-14, May 1990.

[4] J.-J. van de Beek, O. Edfors, M. Sandell, and S. K. Wilson, "On channel estimation in OFDM systems", *Proc. 45th IEEE Vehicular Technology Conf.,* Chicago, IL, July 1995, pp. 815-819.

[5] O. Edfors, M. Sandell, and J. -J. van de Beek, "OFDM channel estimation by singular value decomposition", IEEE Trans. Commun., vol 46, no. 7, pp. 931-939, July 1998.

[6] H. Minn and V.K. Bhargava, "An Investigation into Time Domain Approach for OFDM Channel Estimation", *IEEE Trans. on Broadcasting*, vol 46, no. 4, pp 240-248, Dec. 2000.

[7] C. S. Yeh and Y. Lin, "Channel estimation using pilot tones in OFDM system", *IEEE Trans. Broadcasting,* vol. 45, no. 4, pp. 400–409, Dec. 1999.

[8] X. Wang, T. Tjhung, Y. Wu and B. Caron, "SER Performance Evaluation and Optimization of OFDM System with Residual Frequency and Timing Offsets from Imperfect Synchronization", *IEEE Trans. on Broadcasting*, vol 49, no. 2, June. 2003.

[9] ETSI, "Digital video broadcasting (DVB): Framing, channel coding and modulation for digital terrestrial television", ETSI EN300 744 V1.3.1, Aug. 2000.

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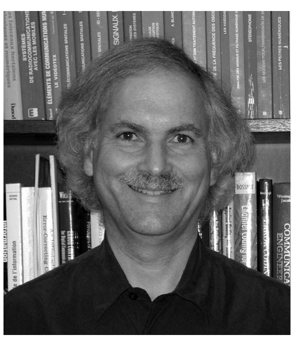

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