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# On coefficient memory co-optimization for channel estimation in a multi-standard environment (LTE and DVB-H)

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***Abstract*—This paper presents a novel memory optimization technique to exploit the analogy between correlation coefficients in MMSE-based channel estimators across multiple standards. The need for coefficient storage for robust MMSE channel estimators is expensive in terms of on-chip memory. Besides, the memory requirements grow linearly by integrating more standards onto one platform. Thus, it becomes inevitable to address the increased on-chip memory problem for such estimators. In this paper, we have shown that by exploiting the inherent similarities between LTE and DVB-H design parameters, a three-fold memory optimization may be achieved with minimal performance loss.**

## I. Introduction

Orthogonal frequency division multiplexing (OFDM) is a driving force behind the latest high speed standards in wired as well as wireless communications. The ability to break a wide spectrum into narrowband subchannels where data could possibly be multiplexed for different users has provided a number of different possibilities, including but not limited to, reducing or eliminating the inter symbol interference (ISI), using simple equalizers and employing flexible channel estimators.

Long Term Evolution (LTE) is the 4th generation standard for mobile wireless communications. It provides high spectrum efficiency with data rates of up to 100 Mbits/s. To facilitate channel estimation, scattered pilots are used in the downlink transmission. As a result, a variety of channel estimation algorithms may be used, as suggested in literature [1].

Similar to LTE, Digital Video Broadcast-Handheld (DVB-H) employs OFDM for data transmission. DVB-H is an evolution of Digital Video Broadcasting-Terrestrial (DVB-T) to address the needs of mobile terminals in time-varying wireless channels. To facilitate channel estimation, scattered pilots are also used in DVB-H. Although the pilot patterns in LTE and DVB-H are different, they both exhibit similarities which may be exploited for co-optimization.

This paper is the continuation of the work started in [2] and followed by [3]. Although the channel estimation techniques presented in this paper are similar to [2], [3], the presented memory optimization principle across LTE and DVB-H in this work binds the proposed estimators into a single channel estimation package. We will show that by exploiting the similarity between the 2nd-order wireless channel statistics across LTE and DVB-H a three-fold on-chip memory reduction associated with the channel estimator filter coefficients can be achieved.

The structure of the paper is as follows. After giving a short introduction to DVB-H and LTE standards in Sec. II, the employed channel estimation approach is briefly discussed in Sec. III. In Sec. IV we show how designing the proposed estimator for specific system parameters allows us to reuse certain coefficients across LTE and DVB-H. Furthermore, it is shown that by designing the estimators for a truncated guard interval in LTE further memory optimization is achieved. Finally, in Sec. V simulation results for the proposed design methods in terms of channel estimation performance are discussed and conclusive remarks are given in Sec. VI.

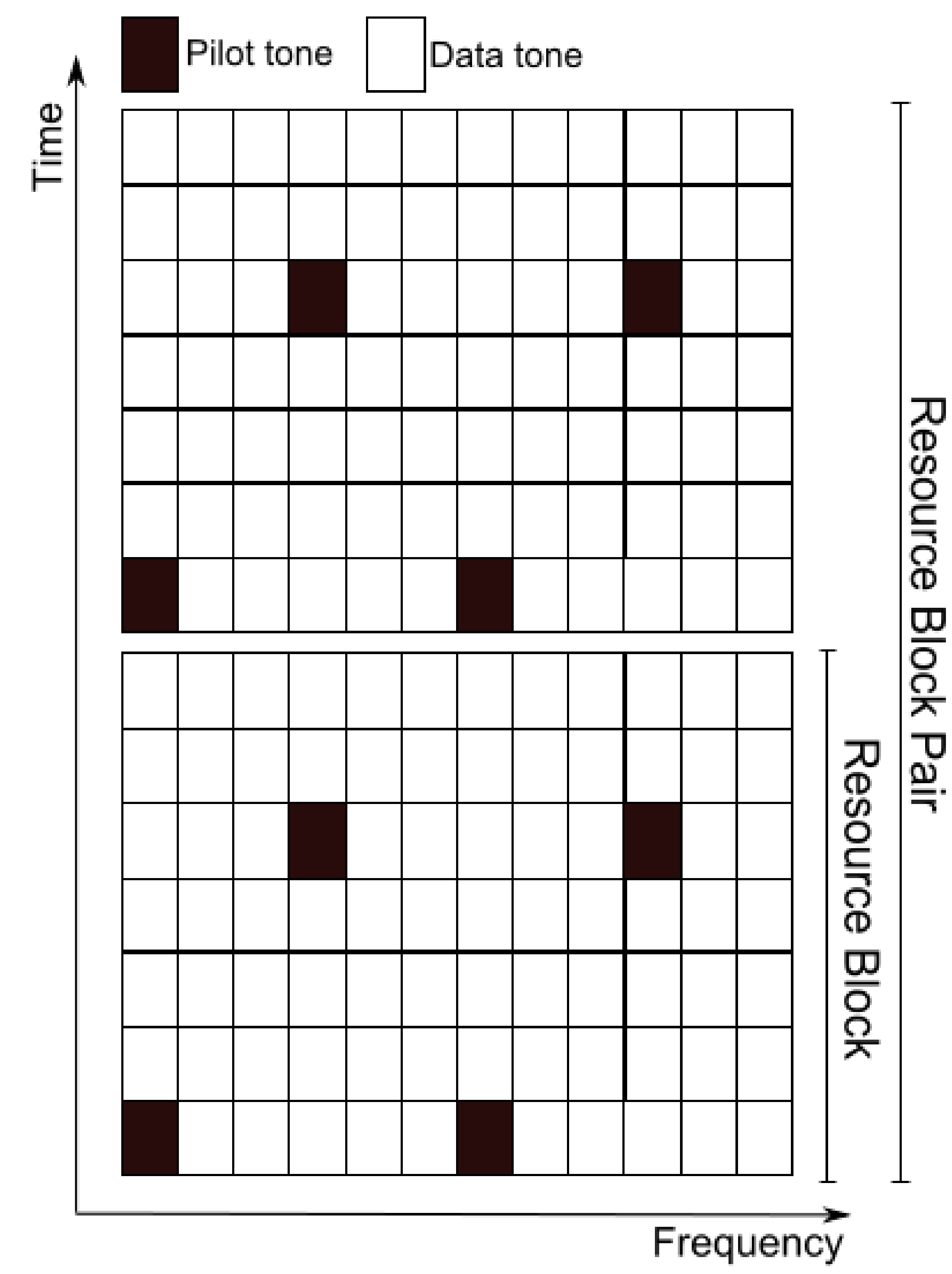


Fig. 1. An example of time-frequency grid corresponding to one RBP for LTE. The scattered pilots are identified by the black boxes.

## II. LTE and DVB-H

LTE exploits the spectrum efficiency provided by OFDM and promises high data rates in wireless communications systems which can be harnessed for various purposes, such as, wireless Internet, high-quality multimedia transmission, etc. It also provides the flexibility for various system implementations through different modes of operation, i.e., different bandwidths (BW). The supported BW range (2-20 MHz) corresponds to DFT sizes of $128 - 2048$ points.

To combat ISI two different cyclic prefixes (CP) are defined for LTE, i.e., *normal* and *extended* CPs each having a length equal to that of the maximum expected delay spread in the wireless channel. The normal CP has a fixed length of $4.69\,\mu$s and the extended CP's spread is equal to $16.67\,\mu$s.

To facilitate channel estimation for such a wide spectrum in a multi-path fading environment, scattered pilots are introduced in the physical layer of LTE. An example of scattered pilots for a resource block pair (RBP) [4] is depicted in Fig. 1. As can be seen the pilots are scattered in both time and frequency, which provides the opportunity to apply various channel estimation schemes.

DVB-H is also an OFDM based system. It is a refinement of DVB-T and is adapted for the needs of mobile communications. Among many different modifications, one can mention the addition

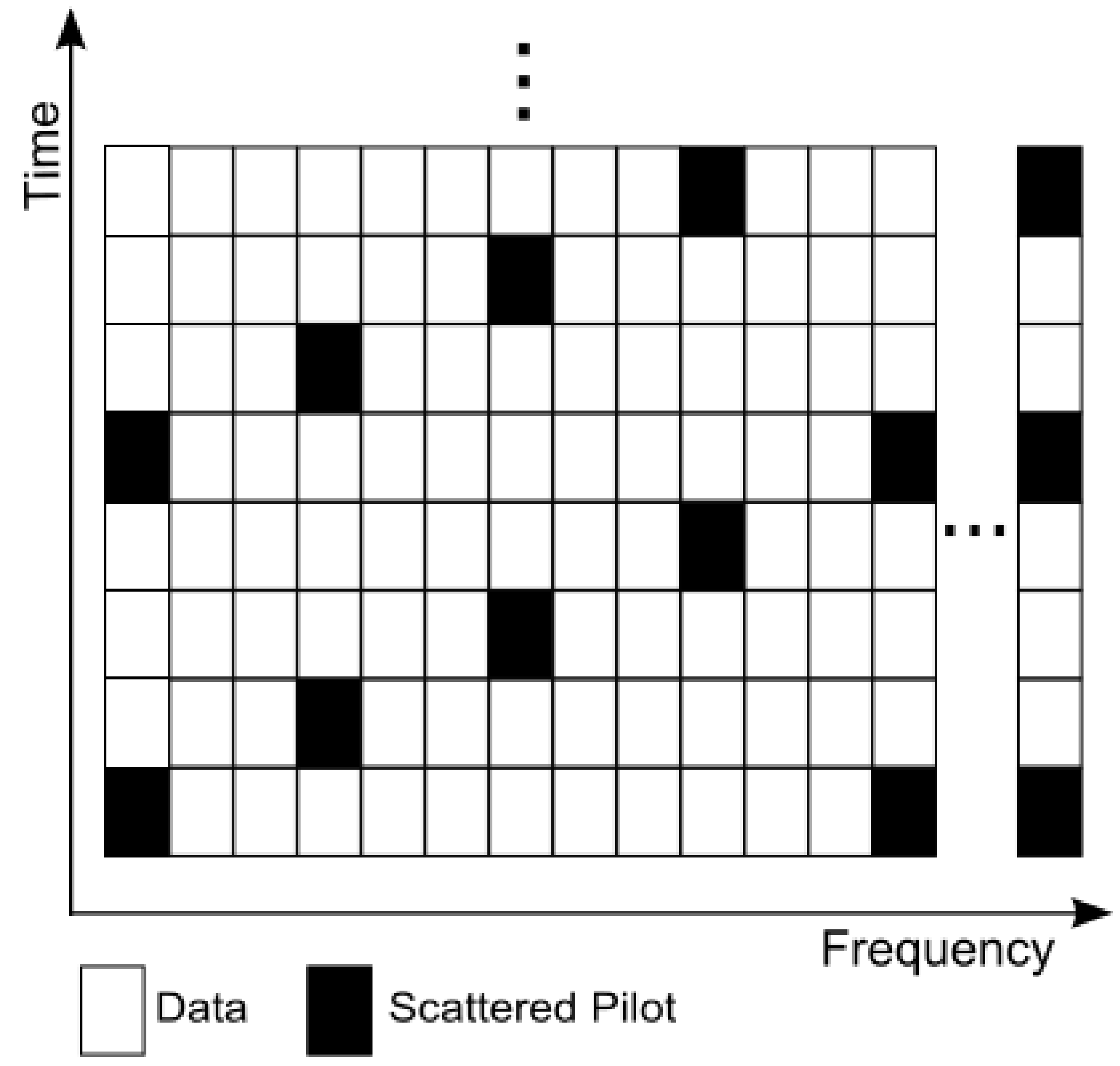


Fig. 2. An example of time-frequency grid for DVB-H. The scattered pilots are identified by the black boxes.

of 4k operation mode which offers an additional trade-off between transmission cell size and mobile reception capabilities[5].

Similar to many other OFDM-based systems different CPs are also standardized for DVB-H. More precisely, there are four different CPs adopted in DVB-H which are known as $1/4$, $1/8$, $1/16$ and $1/32$. The numbers correspond to the ratios of the CP duration and the useful symbol duration.

Scattered pilots are also employed in DVB-H for channel estimation purposes. Fig. 2 illustrates an example of scattered pilots distribution, in time and frequency, for a typical DVB-H system. It can be observed that the pilot density is higher in DVB-H when compared to LTE. This enables the possibility to adopt a wider set of channel estimation techniques, such as various merging schemes elaborated in this paper.

## III. Channel Estimation

A number of techniques can be used for pilot-assisted channel estimation in LTE and DVB-H. Depending on the estimators complexity-performance trade-off, several algorithms may be used in practice [6]. In [2], [3] the concept of a modified robust MMSE (MRMMSE) estimator is introduced. The MRMMSE enables low-complexity channel estimation with an acceptable performance in fading environments specified by LTE standard [4].

Considering a wide sense stationary uncorrelated scattering (WSSUS) environment our wireless channel, composed of M impulses with a certain power delay profile (PDP), $\Theta(\tau_l)$, is modeled as

$$h_{\text{cont.}}(\tau) = \sum_{l=0}^{M-1} \alpha_l \delta(\tau - \tau_l T_s), \tag{1}$$

where $\alpha_l$ are zero-mean complex Gaussian random variables and $T_s$ is the system's sampling interval. Furthermore, the channel attenuation on tone $k$ for the above channel model becomes,

$$h[k] = \sum_{l=0}^{M-1} \alpha_l \exp(-2\pi j (k/N)\tau_l). \tag{2}$$

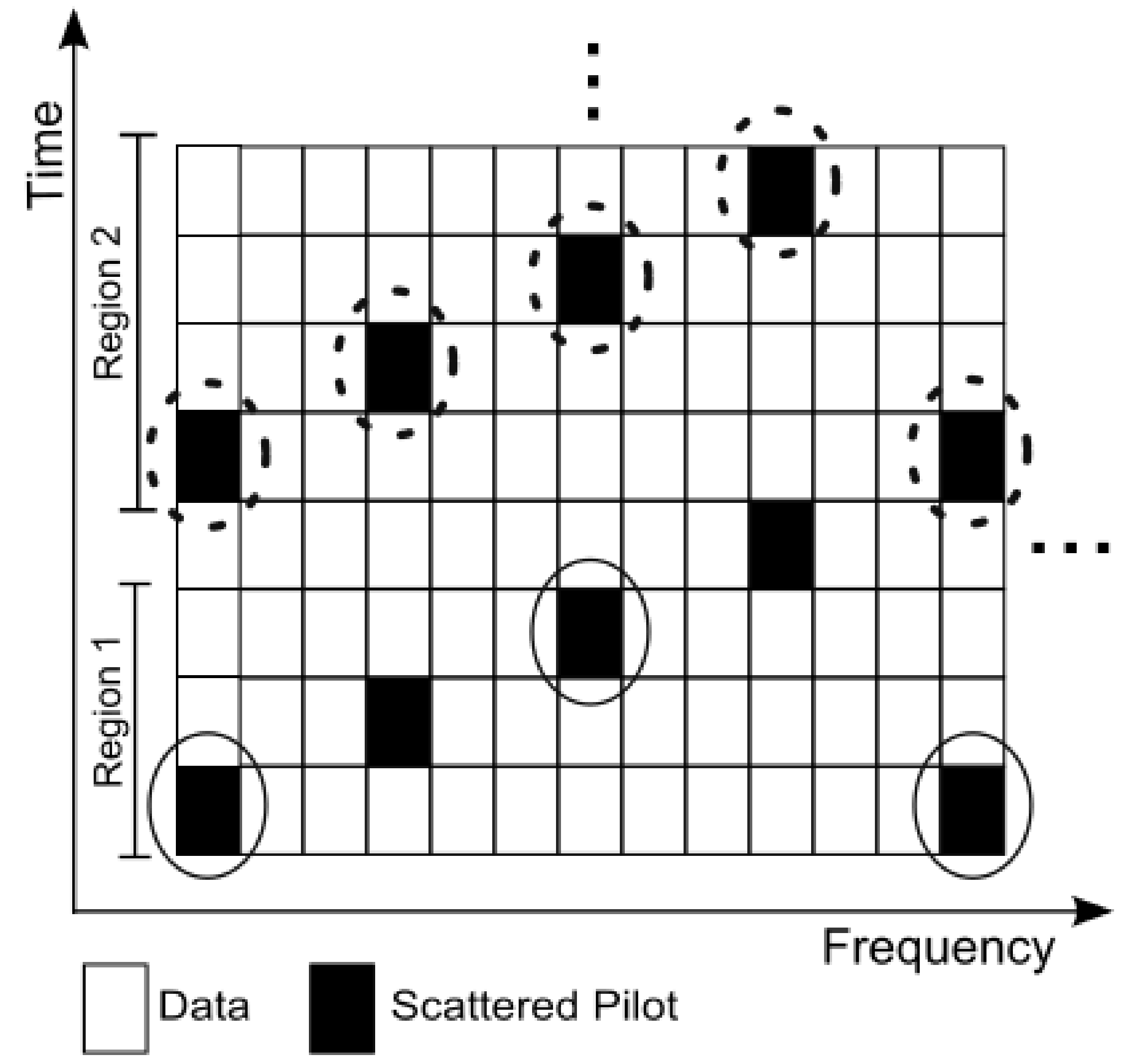


Fig. 3. An example of time-frequency grid for DVB-H. The scattered pilots are identified by the black boxes. The solid circles show how pilots from three consecutive OFDM symbols are collected to construct a pilot vector with a pilot separation of 6. Similarly, the dotted circles identify the pilots collected from four consecutive OFDM symbols resulting in a pilot vector with a separation of 3.

If the subcarriers, including both pilots and data carrying tones, corresponding to one OFDM symbol are collected into a single column vector at the receiver, we can model the received vector as,

$$\mathbf{y} = \mathbf{X}\mathbf{h} + \mathbf{w} \tag{3}$$

where $\mathbf{y}$ is the received data column vector of size $N$, $\mathbf{X}$ is a diagonal matrix of size $N \times N$ encompassing the transmitted data, $\mathbf{h}$ and $\mathbf{w}$ are column vectors of size $N$ containing the channel attenuations and the independent and identically distributed (IID) white Gaussian noise values respectively. Moreover, let $(.)^H$ denote the Hermitian transpose, then the 1-D MMSE-based channel estimation in frequency for the above model is given by the following equation,

$$\hat{\mathbf{h}}_{\text{mmse}} = \mathbf{R}_{hh_p} \left( \mathbf{R}_{h_p h_p} + \frac{1}{\text{SNR}} \mathbf{I} \right)^{-1} \hat{\mathbf{h}}_{\text{p,ls}} \tag{4}$$

where $\hat{\mathbf{h}}_{\text{mmse}}$ is a column vector of size $N$ containing the estimated channel tones and $\mathbf{h}_p$ is a column vector of size $N_p$ encompassing the sampled channel at the pilot positions. Moreover, $\mathbf{R}_{h_p h_p} = \mathbb{E}[\mathbf{h}_p \mathbf{h}_p^H]$ is a matrix containing the autocorrelation values of the sampled channel on the pilot positions, $\mathbf{R}_{hh_p} = \mathbb{E}\left[\mathbf{h}\mathbf{h}_p^H\right]$ is the cross-correlation matrix between the pilot tones and subcarriers and SNR is the signal-to-noise ratio. Furthermore,

$$\hat{\mathbf{h}}_{\text{p,ls}} = \mathbf{X}_p^{-1} \mathbf{y}_p \tag{5}$$

is the least squares (LS) estimate of the channel attenuations $\mathbf{h}_p$ on the pilot tones, where $\mathbf{X}_p$ is a matrix containing the transmitted pilot data on its diagonal and $\mathbf{y}_p$ is the column vector of received pilot tones.

To avoid computationally expensive matrix inversions imposed by (4), a robust estimator may be used which has been shown to exhibit acceptable performance [2]. The robust estimators may be designed for a set of fixed channel estimation parameters, e.g., SNR and 2nd order channel statistics. For instance, the frequency correlation, corresponding to the channel model in (1), between two subcarriers, with a spacing of $\Delta k$, depends on the PDP, $\Theta(\tau_l)$, of the channel. Furthermore, for a uniformly distributed PDP the frequency correlation amounts to [7]

$$r_h[\Delta k] = \frac{1-\exp(-2j\pi L\Delta k/N)}{2j\pi L\Delta k/N}, \quad (6)$$

where $L$ is the delay spread of the wireless channel in samples. It can be seen in (6) that the correlation among subcarriers in a single OFDM symbol depends only on the distance between the corresponding subcarriers ($\Delta k$), the PDP length ($L$), and the number of DFT points ($N$). As we will see in the following sections, the ratio between the above parameters facilitates co-optimization of filter coefficients across LTE and DVB-H.

It can be shown [2], [3] that due to correlation loss among the subcarriers located far apart, using only a few pilots in the vicinity of each subcarrier provides an acceptable performance in terms of channel estimation. Doing the estimation as such, not only lowers the computational complexity of the estimator but also reduces the coefficient memory requirements [3].

In [3] it has been shown that by combining the above mentioned strategy, i.e., using a subset of pilots, and the pilots merging scheme, low-complexity estimators, called modified robust MMSE (MRMMSE) can be developed. Moreover, these estimators exhibit an acceptable performance in moderately fast fading environments for LTE [3]. Likewise, the same principle may be applied to DVB-H [2] with different approaches to pilot merging. Fig. 3 shows how two different pilot merging schemes can be performed for channel estimation using (4).

To construct a pilot vector similar in concept to the one in [3], where the pilot separation is 3, pilots from four consecutive OFDM symbols are collected and merged into a single pilot vector. This is illustrated by dotted circles in Fig. 3. The constructed pilot vector is further used for channel estimation as well as equalization of, say, region 2 in Fig. 3. Similarly, if a pilot separation of 6 is desired, pilots from alternate OFDM symbols, as shown by solid-line circles in Fig. 3, are collected into a pilot vector. The built pilot vector is further fed into the channel estimator whose output is used for equalization of the region encompassed by the pilot contributing OFDM symbols, e.g., region 1 in Fig. 3.

Each pilots merging scheme has its own pros and cons in terms of performance and computational complexity. An elaborate analysis of the computational complexity versus performance is beyond the scope of this paper. However, manipulating the pilots spacing as such provides the opportunity for further coefficient memory optimization discussed in the following sections.

## IV. Coefficient memory co-optimization

As discussed in previous section and elaborated in [2], [3], using a subset of pilots in the vicinity of each subcarrier for estimation purposes already reduces the memory storage requirements for the RMMSE filter coefficients. This may be practiced for each standard, i.e., DVB-H and LTE in this paper, separately. In other words, using the above mentioned approach, 6 different MRMMSE filter coefficient sets should be generated each designed for one specific CP configuration in LTE and DVB-H, i.e., normal and extended CP in LTE as well as 1/4, 1/8, 1/16 and 1/32 CPs in DVB-H.

To enable further memory optimization across the standards, however, one may use the innate similarity between LTE and DVB-H. In Sec. II, it was shown that by fixing the variables in (4),(6)

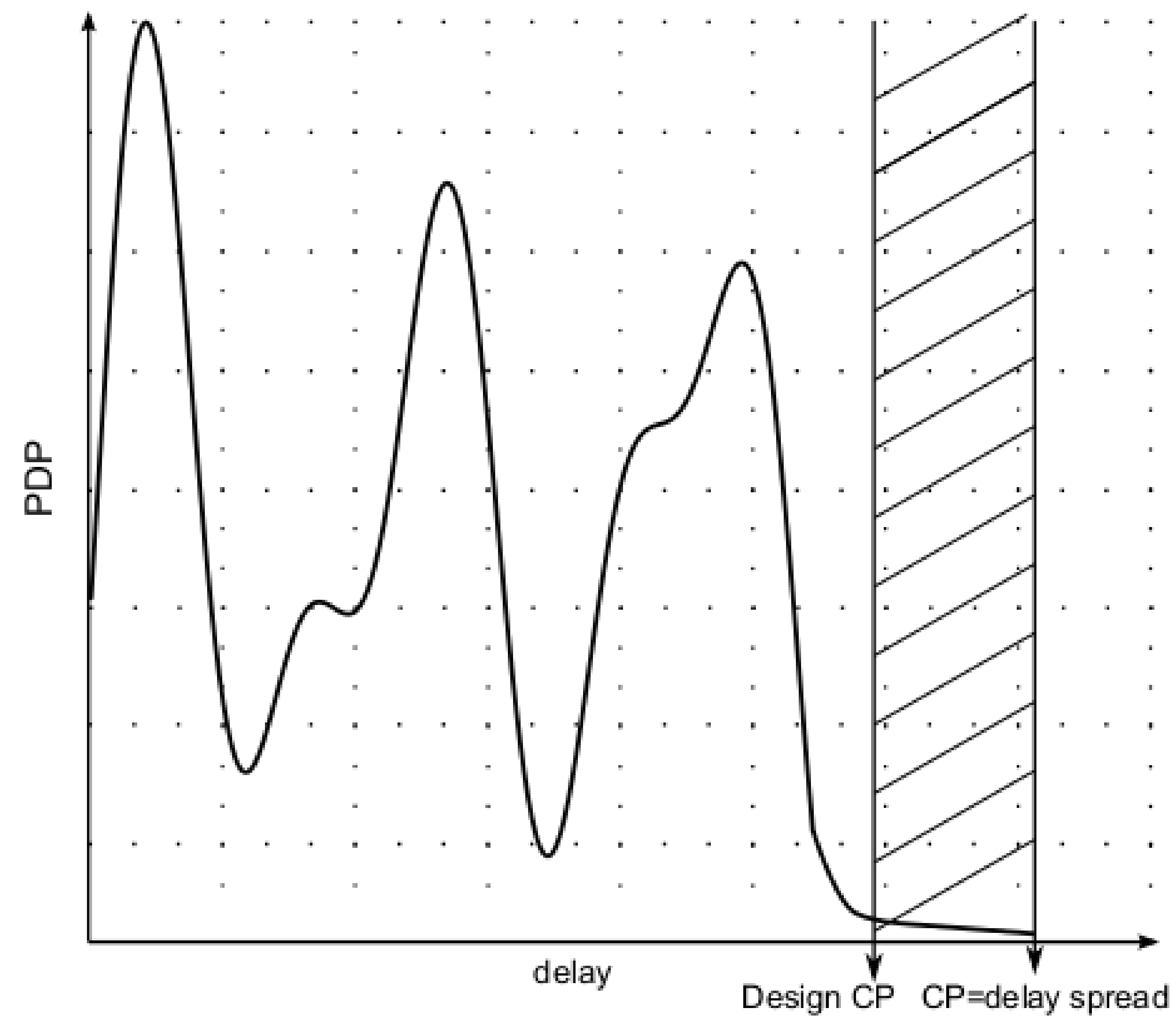


Fig. 4. An example of a wireless channel's PDP. It is expected that the wireless channel's delay spread does not exceed the CP length. The dashed region shows how part of channel energy, though minimal, is ignored during estimator design.

the robust estimator is a function of delay spread of the channel ($L$), subcarrier spacing ($\Delta k$) and DFT length ($N$). Let the robust estimators be designed for a uniform PDP with a length equal to that of the maximum expected delay spread in the wireless channel, i.e., the CP length, then (6) becomes

$$r_h[\Delta k] = \frac{1-\exp(-2j\pi N_{CP}\Delta k/N)}{2j\pi N_{CP}\Delta k/N}, \quad (7)$$

where $N_{cp}$ is the designated CP length.

Considering the fact that pilots from neighboring OFDM symbols, as discussed in previous sections, may be merged to address the channel estimation needs of the terminals, various merging patterns may be practiced in LTE and DVB-H to force the corresponding correlation matrices to be identical. In fact, our intention is to force

$$r_{h_1}[\Delta k] = r_{h_2}[\Delta k],\ \forall k, \quad (8)$$

where index 1 refers to LTE and index 2 refers to DVB-H. As a result, the estimators will be identical for similar values of SNR. By doing so, it is easy to show that it is required that

$$\frac{\Delta k_1 N_{CP_1}}{N_1} = \frac{\Delta k_2 N_{CP_2}}{N_2} \quad (9)$$

for the estimators in LTE and DVB-H to become identical.

One can see that by adjusting the three different variables in (9), i.e., $N$, $N_{cp}$ and $\Delta k$, the same coefficients can be shared between the two standards. For instance, by designing the estimator based on the extended CP in LTE, when the pilot separation is 3, a certain ratio suggested by (9) is achieved which enables reusing the same estimator in DVB-H, across all different BWs and modes of operation, provided that the system is configured for 1/4 and 1/8 CP lengths. Moreover, constrained by (9), a pilot separation of 3 should be practiced for 1/16 CP while the pilot separation in case of 1/8 CP should be kept at 6, see Table I. By doing so the required number of filter coefficient sets reduces to 4 rather than 6.

Nevertheless, to be able to maximize the coefficient co-optimization, even further, the normal CP length in LTE needs to be truncated to $N_{cp,trunc.}$ where $N_{cp,trunc.} = 2^i$ is the largest value that is smaller or equal to $N_{cp}$ and is further used as the basis for the generation of the MRMMSE estimators. These estimators are identified as truncated MRMMSE (TMRMMSE) throughout this paper. Table I shows the different configurations for which the same coefficients across LTE and DVB-H may be reused. It can be seen that by designing the estimators for the truncated normal CP in LTE, the estimators can be shared with DVB-H provided that the system is set-up for 1/16 and 1/32 CP lengths. Furthermore, a pilot separation of 6 and 3 needs to be practiced for 1/32 and 1/16 respectively. One may practice other pilot merging schemes for LTE and DVB-H to force identical estimation coefficients. However, the suggested configuration in Table I not only is optimal in terms of maximum coefficient optimization but also is in-line with [3] in terms of the channel estimator's performance in fast fading environments.

Designing the robust estimator for a truncated CP provides a two-fold memory co-optimization. In other words, it further reduces the number of filter coefficient sets from 4 to 2. However, it may result in a loss in the channel estimator's performance if the delay spread of the wireless channel exceeds the length of the truncated CP. Fig. 4 illustrates how part of channel energy is ignored during estimator design for an exemplary continuous time wireless channel. However, we expect that the discarded channel energy is minimal for the majority of the wireless channels in practice, specially because the required truncation is minimal. On the contrary, the performance of the estimators may even improve if the root mean squared (rms) delay of the wireless channel is considerably smaller than the CP length. As a result, due to the mismatch reduction between the actual and design PDP the channel estimator's performance for such cases slightly improves.

TABLE I
THE CONFIGURATIONS FOR WHICH COEFFICIENT CO-OPTIMIZATION IS FEASIBLE ACCORDING TO OUR PROPOSED SCHEME.

| LTE | | | | DVB-H | | | |
|---|---|---|---|---|---|---|---|
| $N_{DFT}$ | $N_{cp,trunc.}$ (normal) | $N_{cp}$ (Extended) | Pilot Sep. | BW (MHz) | Mode (k) | CP len. | Pilot Sep. |
| 128-2048 | 8-128 | N.A. | 3 | 6-8 | 2-8 | $\frac{1}{32}$ | 6 |
| | | | | 6-8 | 2-8 | $\frac{1}{16}$ | 3 |
| 128-2048 | N.A. | 32-512 | 3 | 6-8 | 2-8 | $\frac{1}{8}$ | 6 |
| | | | | 6-8 | 2-8 | $\frac{1}{4}$ | 3 |

## V. SIMULATION RESULTS

Estimator performance results for LTE, when the pilot merging scheme with a separation of 3 is adapted, are discussed in [2], [3]. The provided simulations provide a good insight into the performance of such estimators when coefficients are generated for a normal CP without truncation. They also depict a detailed picture of the estimator's performance, in different fading environments, when the proposed pilots merging schemes are practiced.

TABLE II
SYSTEM SIMULATION PARAMETERS.

| Standard | N | $F_c$, [GHz] | V, [km/h] | Modulation | Channel model | Fading model |
|---|---|---|---|---|---|---|
| LTE | 512 | 2.2 | 50 | 4QAM | 3GPPTUx [8] | 2-D, Jake's |
| DVB-H | 2048 | 0.75 | 10-200 | 4QAM | TU-6 [5] | 2-D, Jake's |

Fig. 5 shows the MSE performance of the two estimators designed based on the normal and truncated CP. It can be seen that the MSE difference between the two is quite small. This is in agreement with the discussion about the minimal mismatch introduced by truncation in section IV. In fact, TMRMMSE estimators exhibits a better performance for this specific simulation environment where one of the standard ITU-R 3G [8] channel models, i.e., 3GPPTUx has been adopted. This is mainly due to the fact that not only the rms delay spread of the channel is considerably smaller than the CP length but also there is no resolvable multi-path component in the discarded area, as in Fig. 4. As a result, the mismatch between the design and actual PDP is improved resulting in an slightly improved channel estimation performance.

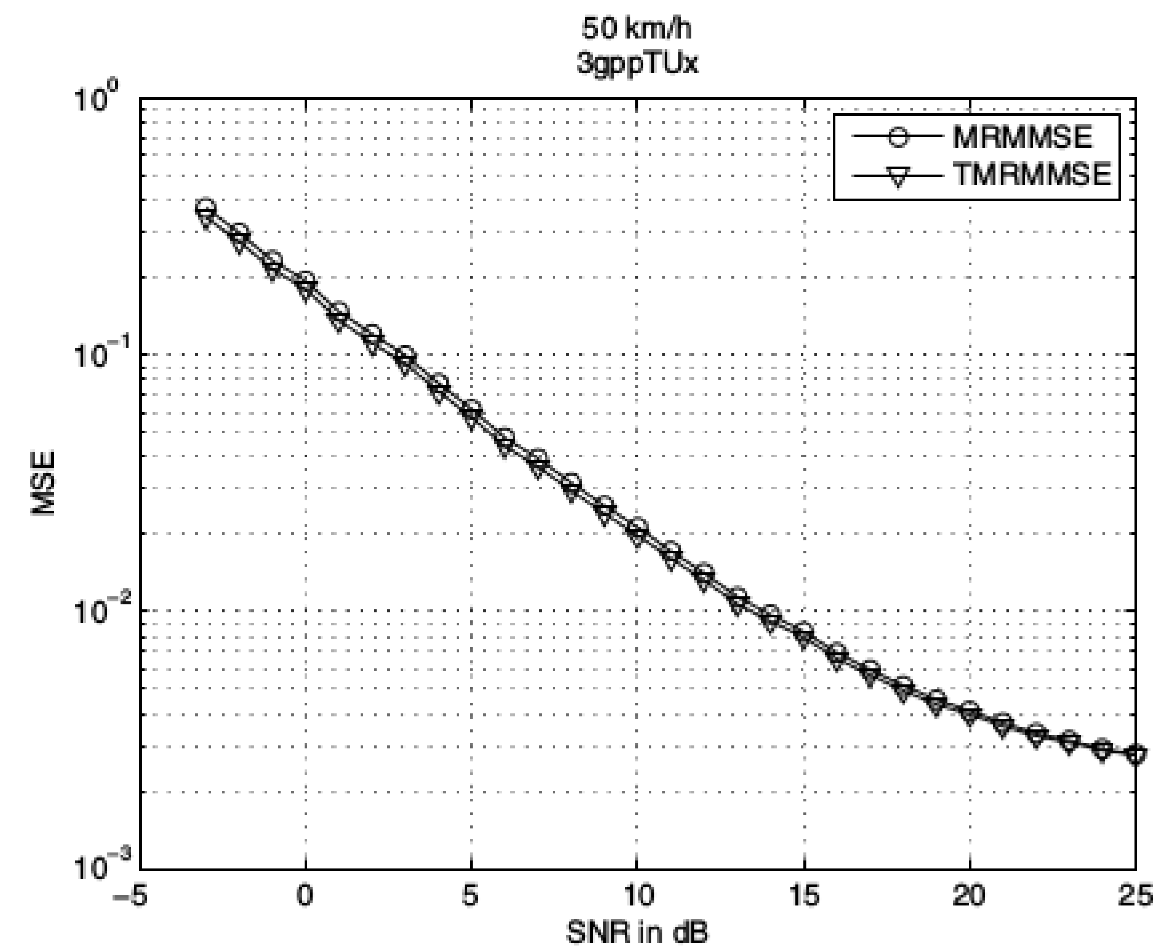


Fig. 5. LTE channel estimator performance in terms of MSE. The difference in MSE between MRMMSE and TMRMMSE is minimal. The observed MSE floor in the high SNR region is because of the channel estimators mismatch with respect to both fading and PDP.

Fig. 6 shows how the performance of the estimator in terms of uncoded bit error rate (BER) is affected. In fact, the TMRMMSE BER curve overlays the MRMMSE which supports the minimal MSE difference observed in Fig. 5. Furthermore, although not included in this paper, the performance of TMRMMSE for all the different standardized channel models, ITU-R 3G channel models [8], have been performed and the comparisons show similar behavior. On the whole, unless the wireless channel in practice has strong taps located in the to-be-discarded region, as depicted in Fig. 4, the TMRMMSE performance takes after the MRMMSE, i.e., without any CP truncation.

Although, no CP truncation is required during DVB-H estimator design, the estimator's performance results need to be discussed due to the application of various pilot merging schemes. As elaborated in [3] for LTE, pilots merging results in different performance and complexity trade-offs. The impact is specifically more visible in fast fading environments. In Fig. 7 the performance of the MRMMSE estimators for two different pilots merging schemes, i.e., pilot separations of 3 and 6 are illustrated. Although, coefficient optimization for pilot separation of 12, i.e., with no merging, is not discussed in this paper, its performance result provides a valuable reference for comparison purposes.

It is evident from Fig. 7 that different merging schemes provide a certain gain/compromise in terms of the required SNR for various fading environments. Besides, there is a significant loss in the estimators performance when the terminal speed increases beyond a certain limit. However, if the performance constraints for the fast fading environments are arbitrarily based on the requirements set by LTE, i.e., an acceptable performance up to terminal speeds of 120 km/h [4], all the merging schemes proposed in this paper satisfy the

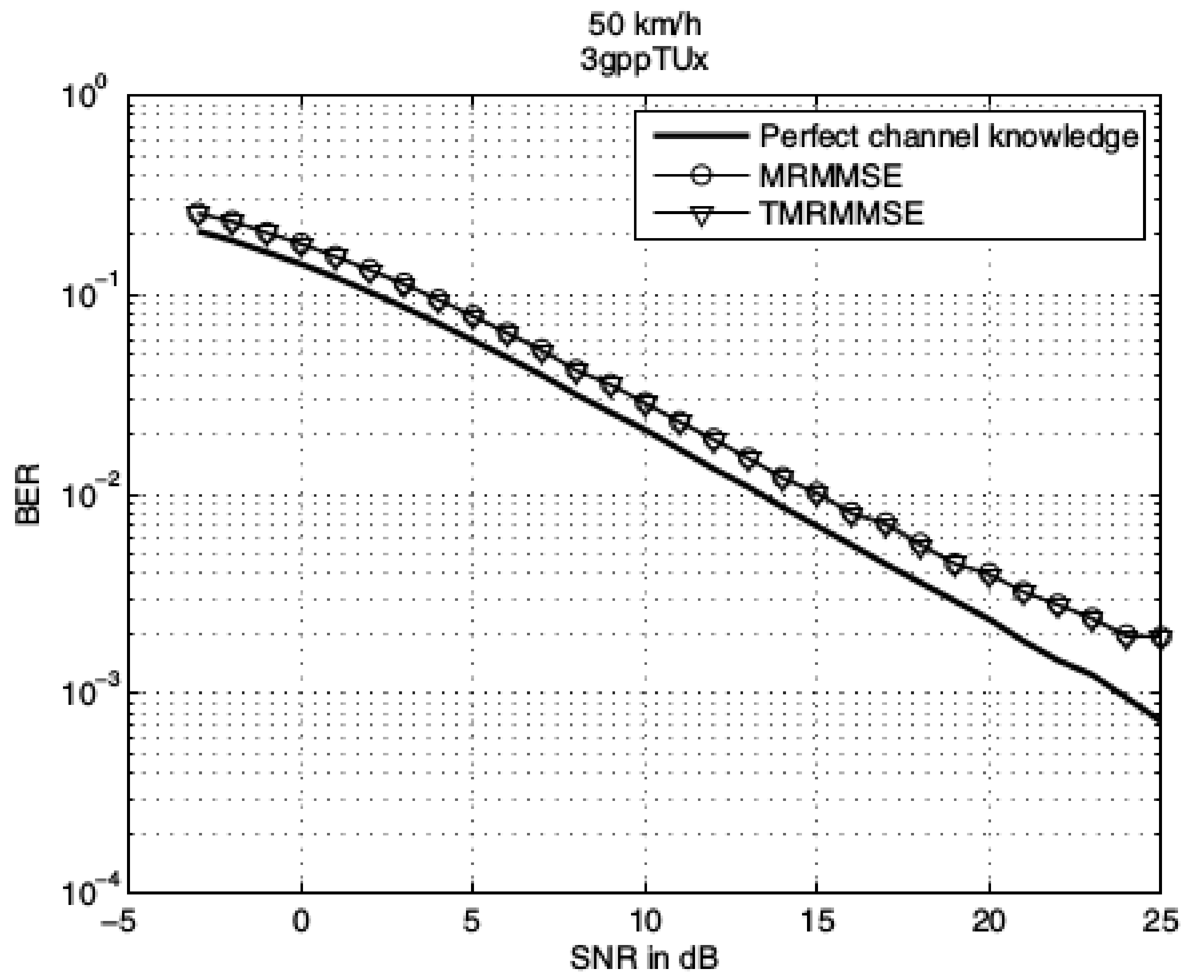


Fig. 6. LTE channel estimator performance in terms of uncoded BER.

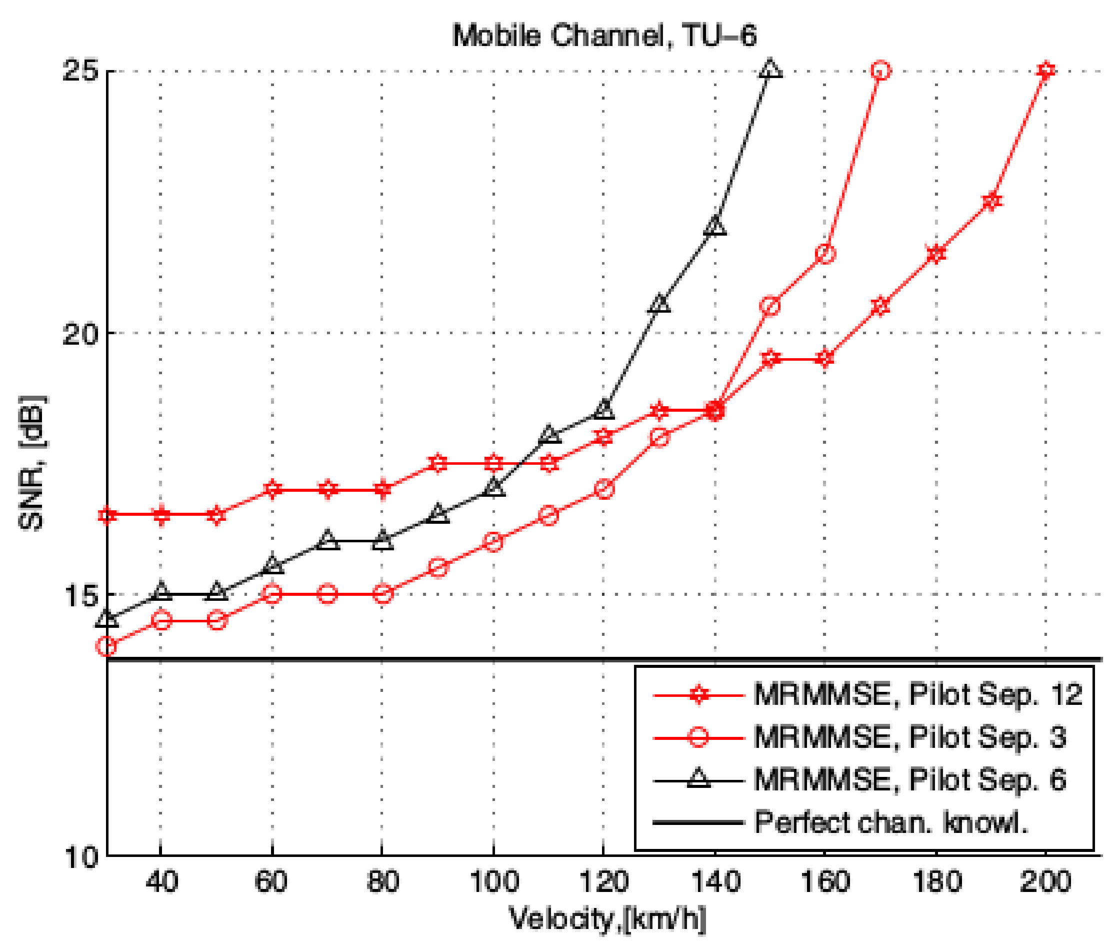


Fig. 7. The required SNR to sustain an uncoded BER of $10^{-2}$ for a range of terminal speeds. The simulations have been done for a carrier frequency of 750 MHz and 4QAM modulation scheme in DVB-H.

requirements of the multi-standard platforms specified by [9]. On the other hand, the proposed practice in this paper, enables a three-fold coefficient memory reduction, 2 rather than 6 filter coefficient sets, when both LTE and DVB-H are co-implemented.

## VI. Conclusion

We have shown that by employing various pilots merging schemes in DVB-H while designing the MRMMSE estimators for a truncated normal CP in LTE, it is possible to optimally share the MRMMSE estimators between LTE and DVB-H. In other words, having the estimators designed for LTE enables the integration of DVB-H standard on the same platform without any additional filter coefficient memory cost. In effect, the on-chip memory requirement for the storage of the robust estimation coefficients in a multi-standard platform considerably decreases. For co-implementation of LTE and DVB-H the on-chip coefficient memory is reduced by a factor of three. Although, the above mentioned procedure forces specific pilot merging patterns for a number of configurations in a given standard, the simulation results show that the performance loss is acceptable for slow as well as moderately fast fading environments.

## VII. Acknowledgments

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