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Low Complexity Channel Estimation for low-mobility LTE using 4×4 MIMO

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Abstract—**Multiple-input multiple-output (MIMO) is a mandatory feature of the Third Generation Partnership Project (3GPP) Long Term Evolution. This work investigates the performance of a low complexity channel estimator for LTE terminals with an emphasis on the 4×4 multiple antenna scheme. The presented work extends a promising low-complexity 2×2 MIMO channel estimator to the 4×4 MIMO case and evaluates its performance at different terminal speeds. The evaluation is done in terms of simulated error performance for coded LTE. We show that the presented channel estimator can be used without a significant performance loss up to about $15 - 20$ km/h, where the approximations done to achieve low complexity start to have a significant impact on the performance.**

I. Introduction

The Long Term Evolution (LTE) [1] as presented by the Third Generation Partnership Project (3GPP) [2] has recently been introduced to the market with promises of increasing data rates for mobile users by an order of magnitude. Both base station and terminal equipment are, however, still in the early stages of evolution and fine tuning of their efficiency will continue for many years. The physical layer of the LTE down-link is based on the combination of Orthogonal Frequency Division Multiplexing (OFDM) and multiple-input multiple-output (MIMO) antenna techniques. OFDM is a rather mature technology which has been used in several other standards, e.g., in the IEEE 802.11 family [3] and for Digital Video Broadcasting-Handheld (DVB-H). OFDM technology can efficiently deliver high data rates over time-dispersive channels. The combination of OFDM and MIMO holds promise for even higher data rates and/or better error performance over the same time-dispersive channels, with exploitation of the spatial domain.

The overall aim of LTE is to improve the capacity of 3rd generation mobile systems to fulfill the increasing demand for higher data rates in the long term. The LTE based terminals should provide the peak data rate of at least 100 Mbps and 50Mbps, respectively, in down-link and up-link [4]. Hence, LTE employs multiple antennas techniques, which have the potential of achieving significantly higher spectral efficiency in rich multipath environments.

The digital receiver in an LTE terminal has to perform many different processing steps to successfully receive and detect the transmitted data. Like single-carrier systems with single-input single-output (SISO) antenna configurations, there are time synchronization, frequency synchronization, channel estimation, and decoding of error-correction codes – just to mention a few. With MIMO these processing tasks become more critical than ever, both due to the sheer increase in data rates and due to the increased complexity of algorithms needed to exploit the spatial domain.

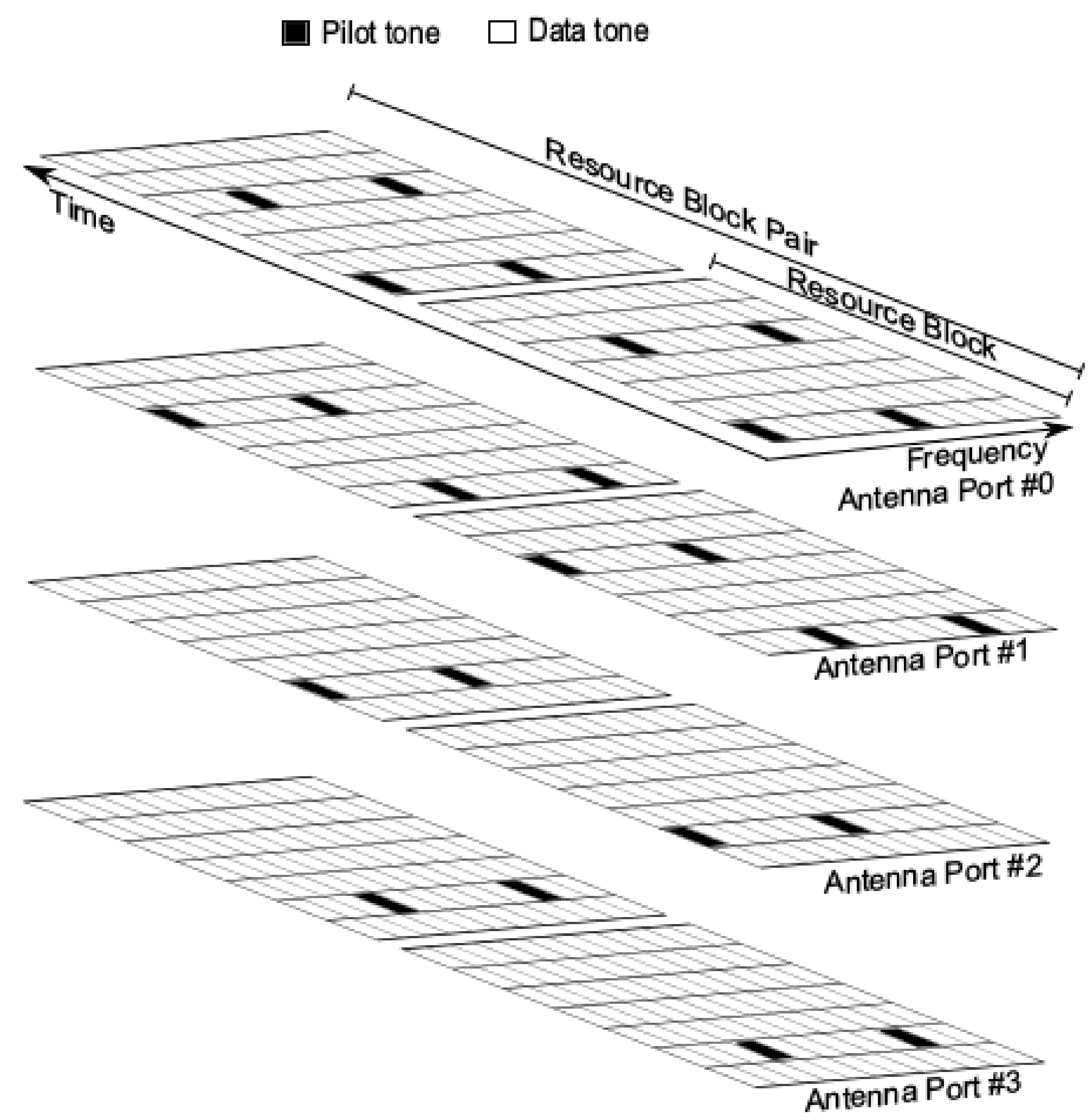

Fig. 1. LTE, scattered pilot structure for 4×4 MIMO.

In this paper, we focus on the channel estimation of an LTE terminal operating in 4×4 MIMO, using spatial multiplexing to achieve high data rates. We assume that this scenario is likely to happen in low-mobility environments with strong time correlation. This can be exploited to reduce channel estimation complexity, as was shown in [5] where a receiver for the combination of LTE and DVB-H was addressed. In this paper, we extend the results for 2×2 MIMO [6] to the 4×4 MIMO case for LTE, evaluate the error performance for different terminal velocities, and determine the range of mobility for which our low complexity channel estimator can support performance close to that of known channel at the receiver.

The organization of the remainder of the paper is as follows. Section II briefly introduces LTE. Section III describes the

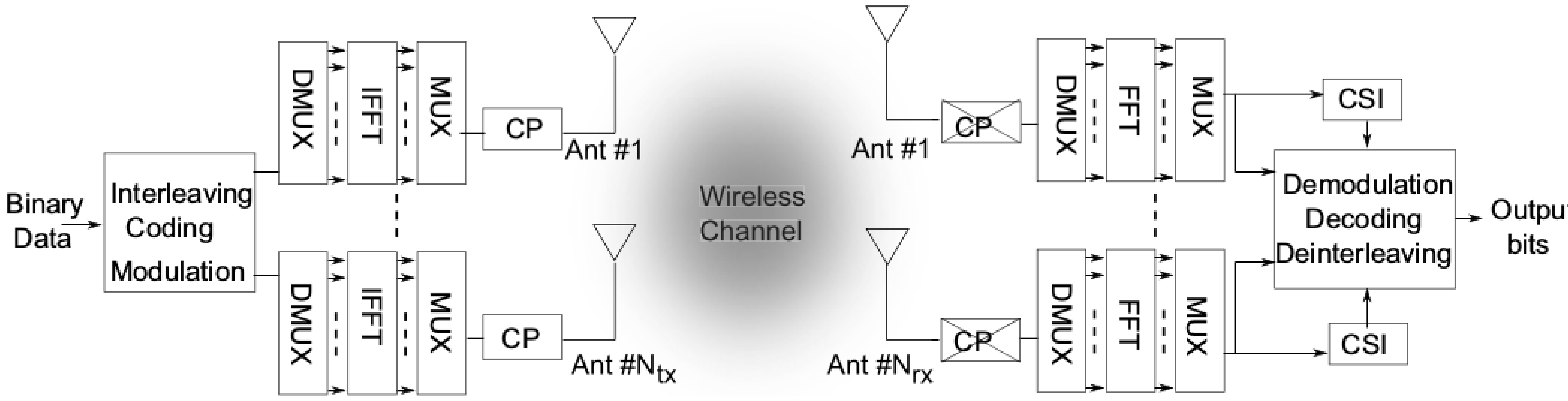

Fig. 2. LTE, simplified MIMO system model.

employed system model, while the channel estimation methods are discussed in Section IV, and performance results based on computer simulations are provided in Section V. Finally, conclusions are drawn in Section VI.

II. Long term evolution (LTE)

LTE employs scattered pilots in the down-link in order to assist the channel estimation. In the subcarriers where one antenna port transmits the pilot, other transmit antenna ports remain silent. As a result, at the receiver the subchannel between each transmit/receive antenna pair can be estimated individually, which makes it straightforward to apply the channel estimation methods for a SISO system to its MIMO counterpart.

In LTE, the available bandwidth, scalable from 1.4 MHz up to 20 MHz, is divided into a number of units, namely Resource Block (RB). Each RB consists of twelve consecutive subcarriers in the frequency domain and seven OFDM symbols in time domain. At least two consecutive RBs are assigned to each User Equipment (UE) at each time; therefore, the smallest possible allocated data to each UE includes twelve subcarriers and fourteen consecutive OFDM symbols. The number of OFDM symbols in each RB used for the Physical Downlink Control Channel (PDCCH) varies from 1 to 3, which is indicated by Physical Control Format Indicator Channel (PCFICH). Thus, we assume that the channel estimation methods are applied to sixteen OFDM symbols.

In LTE, the pilots associated with one Resource Block Pair (RBP), for the first two antenna ports, are distributed in OFDM symbols 1, 5, 8, and 12, while the pilots are located only in symbols 2 and 9 for the 3rd and 4th antenna ports in the 4×4 MIMO scheme (Fig. 1). In the frequency domain, the pilot spacing is six subcarriers. The number of pilots assigned to the 3rd and 4th antenna ports is half the number used on the first two antenna ports. Although this degrades the channel estimation performance, it is likely to be used in low-mobility scenarios where high data rates are desired.

III. System Model

Before describing the channel estimation methods, the block diagram of the considered MIMO OFDM system with N_{tx} transmit and N_{rx} receive antenna ports is illustrated, Fig. 2. The binary data is interleaved and coded, then the coded bits are modulated using one of the LTE modulation formats, e.g., 4QAM. The modulated symbols are demultiplexed to the transmit antennas. After placing the data and pilots on their assigned subcarriers according to the LTE standard, an IFFT is applied and CP is inserted.

The overall system model of a narrowband MIMO OFDM system at subcarrier k and OFDM symbol l can be described as

$$\mathbf{y}(k,l) = \mathbf{H}(k,l)\mathbf{x}(k,l) + \mathbf{w}(k,l) \tag{1}$$

where

$$\mathbf{y}(k,l) = [y_1(k,l) \cdots y_{N_{rx}}(k,l)]^T, \tag{2}$$
$$\mathbf{x}(k,l) = [x_1(k,l) \cdots x_{N_{tx}}(k,l)]^T, \text{ and} \tag{3}$$
$$\mathbf{w}(k,l) = [w_1(k,l) \cdots w_{N_{rx}}(k,l)]^T \tag{4}$$

are the received signals, the transmitted symbols, and the AWGN noise, respectively, while the MIMO channel matrix between the N_{tx} transmit and N_{rx} receive antennas is

$$\mathbf{H}(k,l) = \begin{bmatrix} H_{1,1}(k,l) & \cdots & H_{1,N_{tx}}(k,l) \\ \vdots & & \vdots \\ H_{N_{rx},1}(k,l) & \cdots & H_{N_{rx},N_{tx}(k,l)} \end{bmatrix}. \tag{5}$$

The wireless channel between transmit/receive antenna pairs are assumed to be uncorrelated in the spatial domain, and each of them (here we suppress the antenna indexes for simplicity) is modeled as as an L tap channel impulse response (CIR)

$$h(t,\tau) = \sum_{m=1}^{L} \alpha_m(t)\delta(\tau - \tau_m), \tag{6}$$

where α_m and τ_m are the mth path complex amplitude and delay, respectively. The corresponding Channel Frequency Response (CFR) at time t, from which we can derive the OFDM subcarrier attenuations in (5), is given by

$$H(t,f) = \int_{-\infty}^{+\infty} h(t,\tau)\exp(-j2\pi f\tau)d\tau. \tag{7}$$

Assuming a WSS-US channel model, the time-frequency correlation function of channel can be written as

$$R(\Delta t, \Delta f) = E[\overline{H(t_0,f_0)}H(t_0+\Delta_t, f_0+\Delta_f)], \tag{8}$$

which, with $\Delta t = 0$, gives us the frequency correlation function, *i.e.*, the Fourier transform of the channel's Power Delay Profile (PDP). Similarly, with $\Delta f = 0$, we get the time correlation function, *i.e.*, the inverse Fourier transform of the channel's Doppler spectrum. We assume a classical Jakes' Doppler spectrum with a time correlation function [7]

$$R(\Delta t, 0) \propto J_0(2\pi\phi_{max}\Delta_t), \tag{9}$$

where $J_0()$ is the zeroth-order Bessel function of the first kind, and ϕ_{max} is the maximum Doppler shift in Hz. Using (9), it can be shown that the coherence time of the channel has an inverse relation to the maximum Doppler shift.

Since we are targeting low-mobility scenarios in this paper, we will assume a low maximal Doppler shift in the design of our low complex channel estimators. Evaluation is, however, also done for higher mobility to illustrate the limitations of the proposed estimators.

IV. Channel Estimation

Different techniques can be applied to the 2-D scattered pilot structure in LTE to estimate the channel. The optimal linear estimator in terms of Mean Square Error (MSE) is the 2-D linear minimum mean squared-error (LMMSE) estimator, which performs 2-D interpolation between pilots in both time and frequency, taking advantage of the full 2-D correlation (8). However, due to the complexity of the 2-D LMMSE, it is rarely used in practice and low complex alternatives are more attractive. Separating the 2-D structure into one 1-D filter in time and one 1-D filter in frequency, the channel estimation can often be done with negligible performance loss, while complexity is reduced significantly [8]. We will use this strategy in combination with the assumption of low mobility as an important part of achieving low complexity. We use a 100% correlation in time over one RBP as the low-mobility assumption, which effectively reduces the time-domain filtering to a time-domain averaging.

To derive the frequency-domain estimation, we denote the vector of initial (least-squares) channel estimates at pilot positions by $\hat{\mathbf{h}}_{p,ls}$ and the auto-correlation matrix of the corresponding channel attenuations by $\mathbf{R}_{\mathbf{h}_p\mathbf{h}_p}$. The channel attenuations on all 12 subcarriers in a resource block are denoted as $\mathbf{h}$, and their cross correlation matrix with the initial pilot estimates is $\mathbf{R}_{\mathbf{h}\mathbf{h}_p}$. The frequency-domain estimation can now be expressed as [9]

$$\hat{\mathbf{h}} = \mathbf{R}_{\mathbf{h}\mathbf{h}_p}\left(\mathbf{R}_{\mathbf{h}_p\mathbf{h}_p} + \frac{1}{\text{SNR}}\mathbf{I}\right)^{-1}\hat{\mathbf{h}}_{p,ls}, \tag{10}$$

where SNR denotes the signal-to-noise ratio on the initial channel estimates at pilot positions and $\mathbf{I}$ is an identity matrix. As mentioned in Section II, LTE does not transmit anything on the other antenna ports, where pilots are transmitted by one of them, which allows individual estimation of the channels from different transmit antennas. Therefore, the initial channel estimates in $\hat{\mathbf{h}}_{p,ls}$ can be calculated by dividing the received signals at those positions by the known transmitted pilot symbols at the same positions. Assuming that the channel

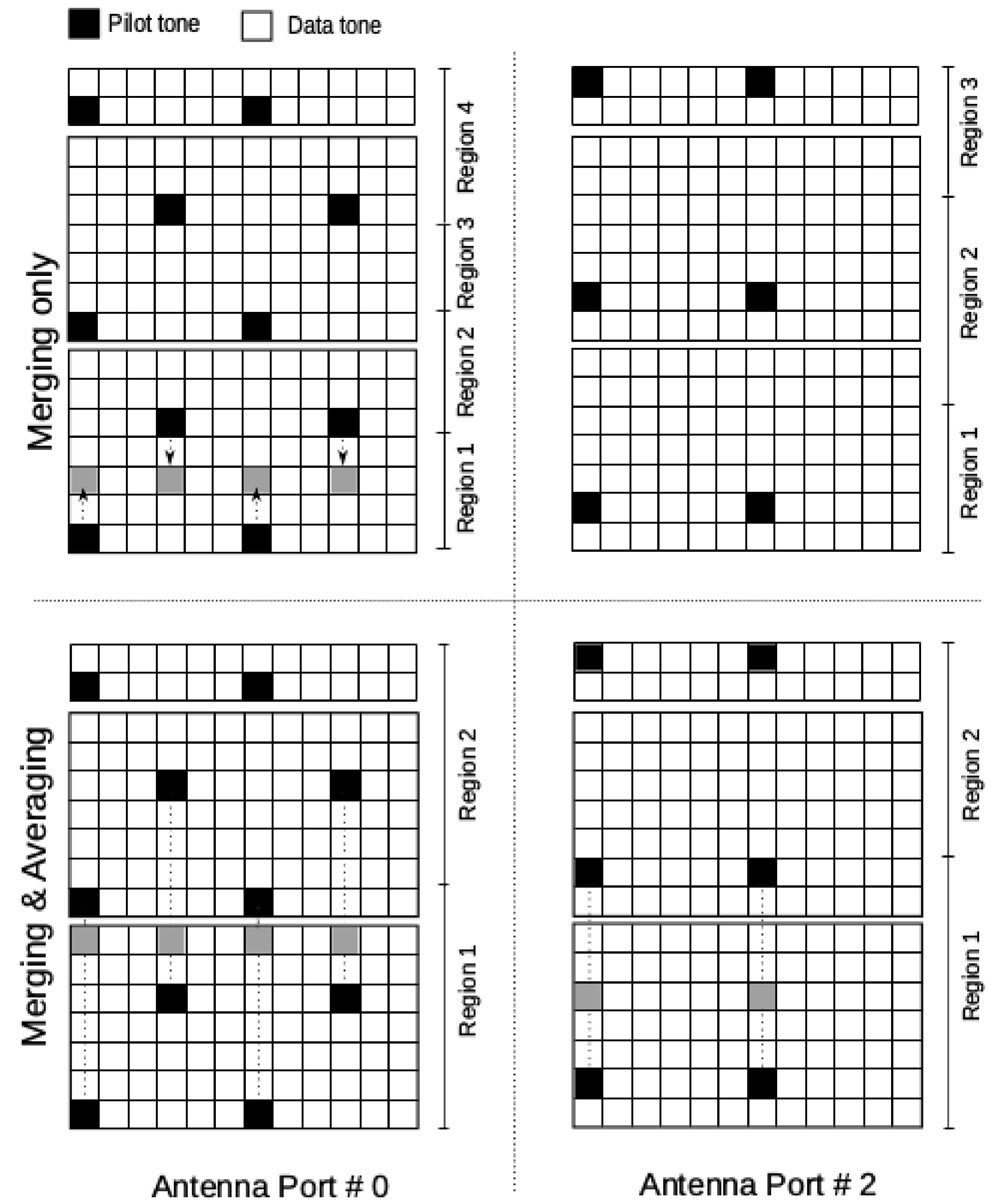

Fig. 3. Principle of merging and averaging. Antenna Port 1 and 3 have the shifted pilot pattern in frequency of Antenna Port 0 and 2, respectively. Besides, the figure depicts only the pilots associated to sixteen OFDM symbols, while the length of pilot vectors used in the proposed estimators in this paper is sixteen.

attenuation $h_{p(j,i)}(k,l)$ between transmit antenna i and receive antenna j at pilot subcarrier k in OFDM symbol l belongs to the set of pilot positions, the initial estimate of it can be obtained by dividing the the received signal $y_j(k,l)$, at receive antenna j, by the known pilot symbol $x_i(k,l)$ at transmit antenna i,

$$\hat{h}_{p,ls(j,i)}(k,l) = \frac{y_j(k,l)}{x_i(k,l)}. \tag{11}$$

With these initial estimates collected in $\mathbf{h}_p$, we are ready to estimate all channel attenuations across one resource block. This is done using (10), which contains a matrix inversion that should ideally be done each time the SNR or the second order channel statistics $\mathbf{R}_{\mathbf{h}_p\mathbf{h}_p}$ changes. We assume both of these fixed and chosen so that the estimator becomes robust to these changes. By doing this, the matrix inversion will be done only once for a fixed SNR as well as a worst case $\mathbf{R}_{\mathbf{h}_p\mathbf{h}_p}$, corresponding to a uniform PDP over the length of the LTE cyclic prefix. Although the performance of this robust LMMSE estimator with a mismatch to the true channel statistics degrades a bit, the complexity reduction is a good motivation why it should be used in practice.

Returning to the time-domain estimation, we note that it is possible to use different 1-D filters in the time domain to generate the initial pilot estimates in $\hat{\mathbf{h}}_{p,ls}$. However, in

	Complexity [mult.]		Memory [byte]	
Est. technique	Port 0/1	Port 2/3	Port 0/1	Port 2/3
Merged pilot	2574	1890	480	384
... with averaging	1422	1314	768	864
Full 2-D LMMSE	51570	25902	1440	1536

TABLE I
ESTIMATOR COMPLEXITY IN REAL MULTIPLICATIONS PER RBP AND MEMORY REQUIREMENTS (BUFFERING) IN BYTE, SEPARATED INTO ANTENNA PORTS 0/1 AND 2/3, WHICH HAVE DIFFERENT PILOT PATTERNS.

order to reduce the complexity of the estimator even further, we have considered two other strategies than traditional 1-D filtering. A simple yet efficient approach is the merged-pilot method, first introduced in [5], and the other one is the merged-pilot method combined with additional averaging to exploit the strong correlation in low-mobility environments. The drawback of the averaging in time is that due to mismatch, its performance for higher mobility is limited. However, the addressed 4×4 MIMO spatial multiplexing scheme for LTE is likely to be used in low-mobility environment and an averaging gain is available in this considered scenario. In LTE, merged-pilot is only applicable in the first two antenna ports, where there are two sets of pilot subcarriers, shifted relative to each other in frequency. Merging (collecting) these two consecutive sets of pilots into one pilot vector $\mathbf{h}_p$ allows us to use a merged pilot pattern that is twice as dense as without the merging process.

Based on the shortest distance to contributing pilot symbols, for the first two antenna ports, each Resource Block Pair is segmented into four regions, Region 1 to 4, as illustrated in Fig. IV for the "Merging only" method. In each region, the same estimated channel is used for equalization of all symbols. In order to improve the performance in the last region, the first two OFDM symbols of the next RB are also considered, which is possible since the receiver has to listen to these too, as discussed in Section II. For antenna ports 2 and 3, no merging is possible, since all OFDM symbols containing pilots have them on the same subcarriers. Hence, the simple piecewise constant method is used for those antenna ports.

In the second method, additional averaging is applied and each RBP is segmented into two regions, Region 1 and 2, as shown in Fig. IV. Using this method, each element of the initial channel estimate vector $\hat{\mathbf{h}}_{p,ls}$ is generated by averaging the contributions from the nearest two OFDM symbols with pilots on a particular subcarrier. Again, the rationale for this is based on the low mobility and large coherence time. For very low mobility, we can expect a 3 dB gain compared to only using the merging strategy. When mobility increases, however, we will suffer from a mismatch and estimator performance degrades. Another side effect of the averaging is that more memory is required, since the use of more pilot symbols in the estimation increases the amount of buffering needed in the receiver.

An overview of the complexity of the different estimation strategies discussed in this paper and their memory requirements, due to buffering, is shown in Table I. The two

FFT size	512	Used tones	300
CP length	36	Pilots/OFDM symbol	50
Δf [kHz]	15	Carrier freq. [GHz]	2.6
PDP	$\exp(-t/9)$	Doppler spec.	Jakes

TABLE II
SIMULATION PARAMETERS USED IN THE EVALUATION OF THE PRESENTED CHANNEL ESTIMATORS.

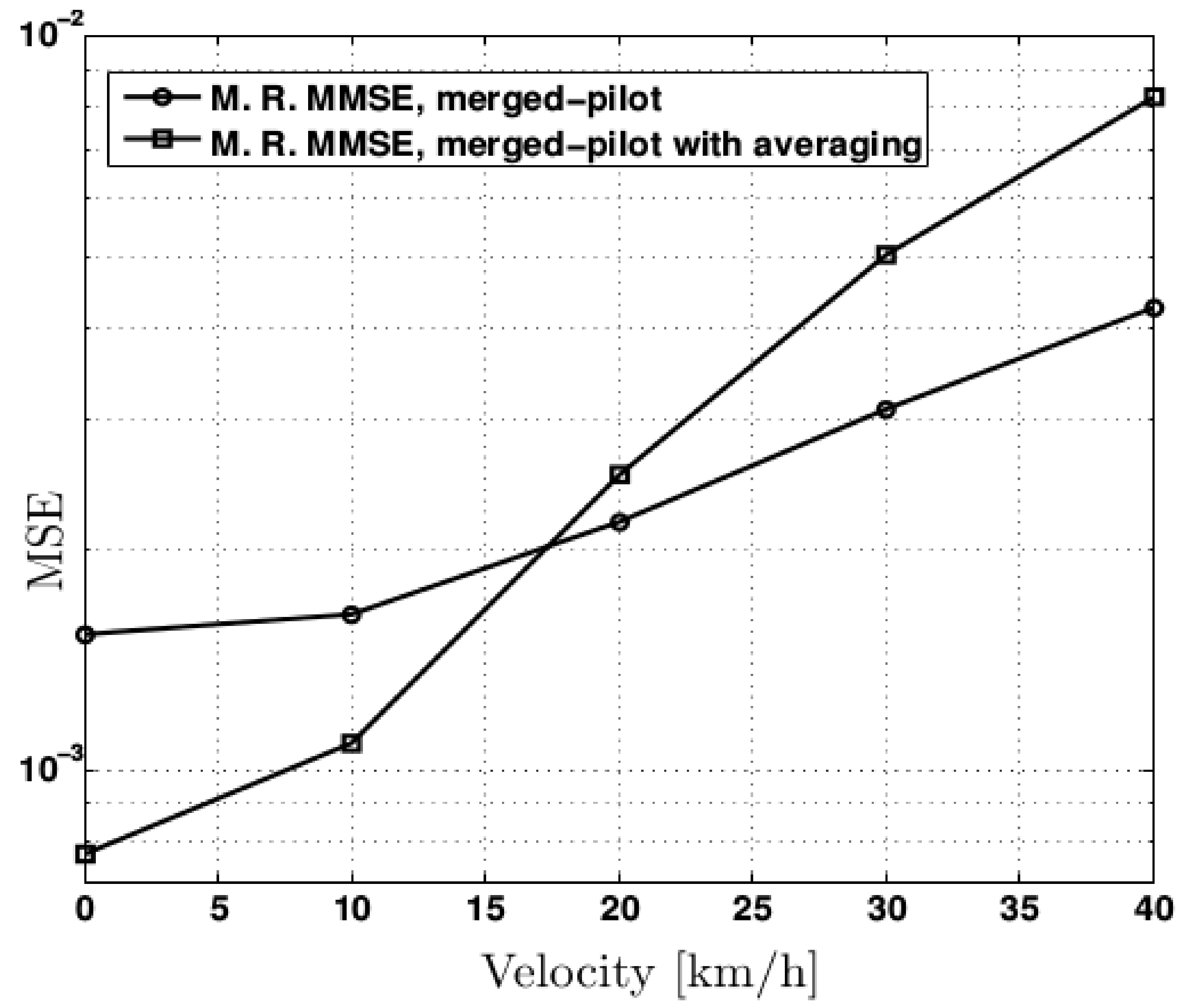

Fig. 4. LTE, *MSE*. The simulations have been done for a *4x4 MIMO* system configured for spatial multiplexing using a ZF receiver for $E_b/N_0 = 20dB$.

proposed low complex estimation strategies show significantly lower numbers on both computational complexity and memory requirements, as compared to the full 2-D LMMSE estimator using the same set of pilots. Having established that we can gain considerably in complexity by introducing merging and averaging, we move on to simulation of system evaluation to compare the performance.

V. Simulation Results

In order to compare the performance of the two low complexity channel estimation methods from Section IV, we simulate an LTE system using these estimators and compare channel estimate MSE and coded Bit Error Rate (BER). The specific simulation parameters used are shown in Table II. The simulations have been performed for a 4×4 MIMO spatial multiplexing scheme with Zero Forcing (ZF) receiver and for a fixed $E_b/N_0 = 20$ dB.

Figures 4 and 5 show simulated MSE and BER for different terminal speeds, respectively. For the BER simulations, we also compare the performance against perfectly known channel. This shows that the low complexity channel estimators discussed in this paper, in terms of BER, are only less than a factor of two away from perfect channel knowledge up to 15 km/h terminal speed. The estimator using both merging and averaging is benefiting from the averaging gain at low

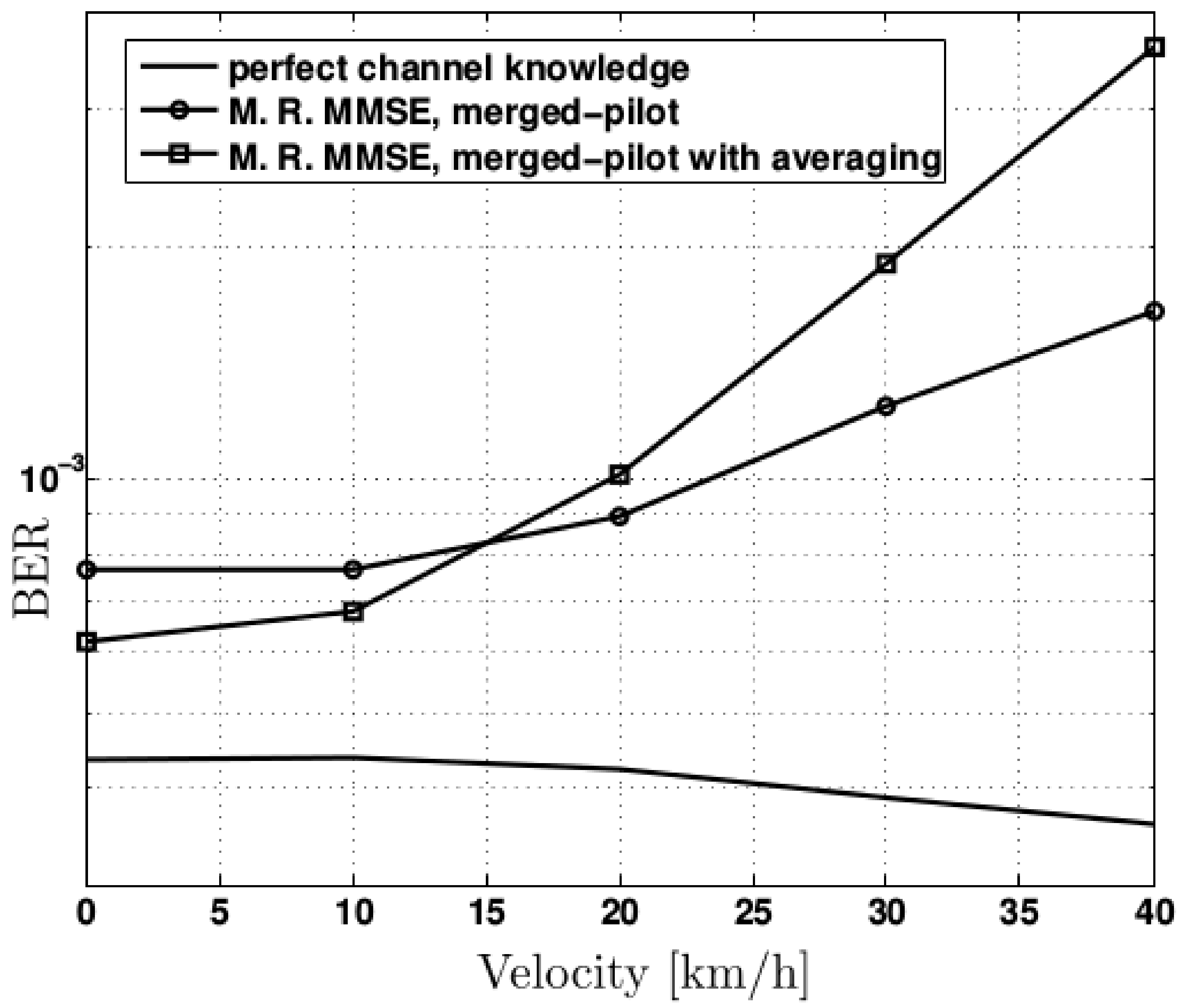

Fig. 5. LTE, coded *BER*. The simulations have been done for a *4x4 MIMO* system configured for spatial multiplexing using a ZF receiver for $E_b/N_0 = 20dB$.

mobility and outperforms the merged-pilot estimator in both MSE and BER up to a terminal speed of around 15 km/h. For higher terminal speeds, though, the decrease in time coherence clearly degrades the performance; therefore, the extra available diversity in the perfect channel knowledge case does not apply to our estimators. At higher terminal speeds, the averaging should be avoided and the merged pilot scheme should be used. However, at low mobility the averaging reduces complexity of the channel estimation, while achieving better performance.

VI. Conclusions

In this paper we have shown that it is possible to save significantly on both complexity and memory requirements for channel estimation in LTE using 4×4 MIMO, as compared to full 2-D LMMSE estimation, while keeping BER performance close to that of known channels for low-mobility scenarios. The new estimator, employing both pilot merging and averaging, will reduce the computational complexity by a factor of thirty (about 40 for antenna ports 0/1 and 20 for antenna ports 2/3) and memory requirements by a factor of two, again as compared to the full 2-D LMMSE estimator using the same pilots.

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