in Proc. IEEE ICC-2003, Anchorage (AK), May 2003, pp. 2406–2410

Space-Time Algorithms for Multiuser Channel Estimation in the Downlink of UMTS/TDD

K. Kopsa, H. Artés, G. Matz, and F. Hlawatsch

Institute of Communications and Radio-Frequency Engineering, Vienna University of Technology
Gusshausstrasse 25/389, A-1040 Wien, Austria
phone: +43 1 58801 38983, fax: +43 1 58801 38999, email: Klaus.Kopsa@nt.tuwien.ac.at

***Abstract*— We present space-time methods for channel estimation in the downlink of a UMTS/TDD system. The channels associated to all base stations near the mobile receiver are estimated by a multiuser, multi-antenna technique. We develop a minimum mean-square error (MMSE) channel estimator that incorporates midamble detection/estimation and least-squares channel estimation as preparatory stages. Combination of this MMSE channel estimator with a successive interference cancellation scheme allows to cope with strong co-channel interference. Simulation results indicate the good performance of our space-time channel estimator for various realistic propagation scenarios.**

I. Introduction

Successful operation of third generation networks for mobile communications requires accurate measurement devices for analyzing the interference situation present. Incorporating space-time signal processing algorithms in such devices allows to analyze the strength and origin of interfering signals. In our work, we develop algorithms that demodulate the broadcast channels (BCHs) of all base stations (BSs) in the vicinity of the mobile receiver (i.e., the measurement device) and extract the cell IDs. Using this knowledge, it is possible to assess the contributions of different BSs to the total interference, thereby allowing network operators to adjust their network accordingly.

Important prerequisites for BCH demodulation are frame synchronization to the different BSs (see [1]) and channel estimation. In this paper, we present space-time methods for multiuser channel estimation in the downlink of a UMTS/TDD system and we assess the performance of these methods.

The paper is organized as follows. After a review of some relevant aspects of the UMTS/TDD standard in this section, Section II presents a minimum mean-square error (MMSE) channel estimator that incorporates midamble detection/estimation and least-squares channel estimation as preparatory stages. To overcome certain performance limitations of this MMSE estimator, Section III proposes the novel *successive cancellation MMSE (SC-MMSE) algorithm* that is a combination of the MMSE estimator with a successive interference cancellation scheme. The performance of the SC-MMSE algorithm is assessed in Section IV.

UMTS/TDD system model. In a UMTS/TDD system, each radio frame consists of 15 time slots as depicted in Fig. 1 [2]. Each time slot can be allocated for uplink or downlink in a flexible manner. As shown in Fig. 2, the time slots consist of two

Funding by the European IST project ANTIUM and by FWF grant P15156.

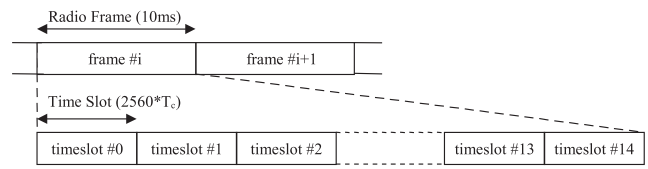


Fig. 1. Physical channel frame structure [2].

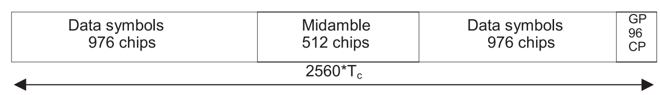


Fig. 2. Time slot structure [2].

data parts separated by a midamble and followed by a guard period. The midamble is used for channel estimation. The data parts contain up to 16 data channels, each spread with a different spreading code [3]. After multiplication by the cell-specific scrambling code, the sum of the spread data channels is transmitted over a frequency-selective fading channel and received on the M-element antenna array of the mobile receiver.

Assuming K BSs and channels with maximum delay $L-1$, the received discrete-time (sampled) base-band signal vector $\mathbf{x}(n)$ of size $M \times 1$ is given by

$$\mathbf{x}(n) = \sum_{k=1}^{K} \mathbf{x}_k(n) + \mathbf{n}(n) \quad \text{with} \quad \mathbf{x}_k(n) = \mathbf{H}_k \mathbf{s}_k(n). \tag{1}$$

Here, $\mathbf{s}_k(n) \triangleq \big[s_k(n)\, s_k(n-1) \ldots s_k(n-L+1)\big]^T$ with $s_k(n)$ the signal transmitted by the kth BS, $\mathbf{H}_k \triangleq \big[\mathbf{h}_{k,0} \ldots \mathbf{h}_{k,L-1}\big]$ is the $M \times L$ channel matrix of the kth BS, and $\mathbf{n}(n)$ is a Gaussian noise vector. Because the UMTS/TDD network is synchronized, the BCHs of all BSs are transmitted in the same time slot. For channel estimation, it suffices to consider $\mathbf{x}(n)$ only in the time interval corresponding to the midamble, which is known from the preceding synchronization stage. For simplicity, we will write this interval as $[1, L_\mathrm{m}+L-1]$, where $L_\mathrm{m} = 512$ is the midamble length. Within this interval, our assumption in (1) that the channel is time-invariant is approximately satisfied if the mobile receiver does not move too fast.

In UMTS/TDD, there are 8 midambles $m_k^{(l)}(n)$ ($l \in \{1,\ldots,8\}$) per BS [2]. These midambles are constructed from a cell-specific "basic" midamble code that is known to the receiver from the synchronization stage. The BCH always uses

0-7803-7802-4/03/$17.00 © 2003 IEEE

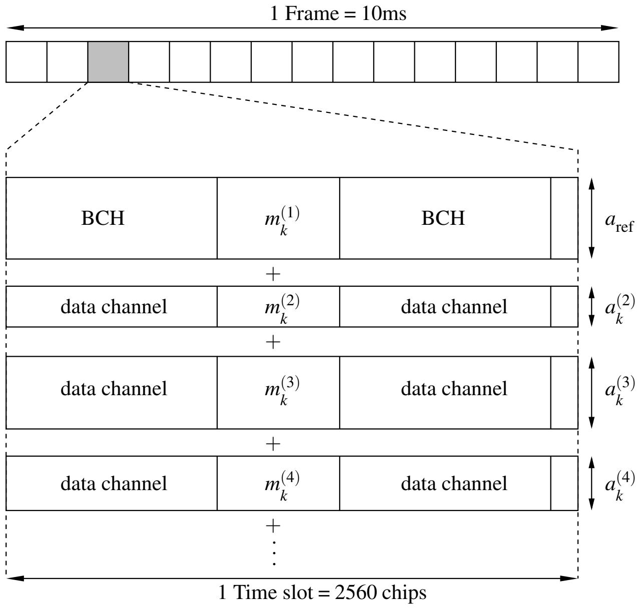


Fig. 3. Structure of a BCH time slot.

$m_k^{(1)}(n)$ and each data channel uses one of the six midambles $m_k^{(3)}(n), \ldots, m_k^{(8)}(n)$; $m_k^{(2)}(n)$ is reserved for transmit diversity, which will not be considered here. The "total midamble" transmitted by the kth BS is thus given by (see Fig. 3)

$$m_k(n) \,=\, a_{\mathrm{ref}}\, m_k^{(1)}(n) + \sum_{l \in \mathscr{L}_k} a_k^{(l)}\, m_k^{(l)}(n)\,, \tag{2}$$

where the index set $\mathscr{L}_k \subseteq \{3, \ldots, 8\}$ specifies the midambles used by the data channels, a_{ref} is the known, fixed amplitude of the BCH midamble, and the $a_k^{(l)}$ are the amplitudes of the data channel midambles. These latter amplitudes are unknown due to the power control of the associated data channels.

II. MMSE Channel Estimation

In this section, we develop the MMSE channel estimator that provides the algorithmic basis for the SC-MMSE channel estimator to be proposed in Section III.

A. Midamble Estimation

Ideally, channel estimation would utilize the total midambles $m_k(n)$ in (2). Unfortunately, the composition of the $m_k(n)$ (i.e., the midamble sets $\mathscr{L}_k$ and midamble amplitudes $a_k^{(l)}$) is unknown at the receiver. Using only the known BCH midamble $m_k^{(1)}(n)$ would be suboptimal because the midambles of the data channels would act as interferers. Thus, prior to channel estimation, we will estimate the total midambles $m_k(n)$ by detecting the sets $\mathscr{L}_k$ and estimating the amplitudes $a_k^{(l)}$.

This detection-estimation problem can be solved by means of a generalized likelihood ratio test (GLRT) [4] approach combined with a maximum likelihood (ML) [5] amplitude estimator. Using a signal model and derivation similar to [1], we obtain the GLRT test statistics

$$c_k^{(l)} \,=\, \frac{1}{L_{\mathrm{m}}}\, \hat{\mathbf{r}}^H_{\mathbf{x},m_k^{(l)}}\, \hat{\mathbf{R}}^{-1}_{\mathbf{x},\mathbf{x}}\, \hat{\mathbf{r}}_{\mathbf{x},m_k^{(l)}}$$

for detection of the individual midambles $m_k^{(l)}(n)$. Here,

$$\hat{\mathbf{R}}_{\mathbf{x},\mathbf{x}} \,=\, \frac{1}{L_{\mathrm{m}}} \sum_{n=1}^{L_{\mathrm{m}}} \mathbf{x}(n)\,\mathbf{x}^H(n)\,, \tag{3}$$

$$\hat{\mathbf{r}}_{\mathbf{x},m_k^{(l)}} \,=\, \frac{1}{L_{\mathrm{m}}} \sum_{n=1}^{L_{\mathrm{m}}} \mathbf{x}(n)\, m_k^{(l)*}(n)\,. \tag{4}$$

The detected midamble index set $\hat{\mathscr{L}}_k$ is defined as the set of indices $l \in \{3, \ldots, 8\}$ for which $c_k^{(l)}$ exceeds a certain threshold η. The choice of η is delicate because it corresponds to a tradeoff of detection probability against false alarm probability: if η is too low, we will detect midambles that are not being used; if it is too high, we will miss some midambles used. However, because the BCH is transmitted with the known, fixed reference amplitude a_{ref}, we can use the value of $c_k^{(1)}$ to adjust η.

For estimation of the midamble amplitudes $a_k^{(l)}$, we propose the following ML approach. By putting all but the lth midamble and the noise $\mathbf{n}(n)$ into an interference vector $\mathbf{w}(n)$ and assuming a one-tap channel $\mathbf{h}_k \triangleq \mathbf{h}_{k,0} = \mathbf{H}_k$, (1) becomes

$$\mathbf{x}(n) \,=\, a_k^{(l)}\, \mathbf{h}_k\, m_k^{(l)}(n) + \mathbf{w}(n)\,.$$

It can then be shown that the ML amplitude estimate equals

$$\hat{a}_k^{(l)} = \frac{1}{L_m}\, \frac{\mathbf{h}_k^H \mathbf{R}^{-1}_{\mathbf{w},\mathbf{w}} \hat{\mathbf{r}}_{\mathbf{x},m_k^{(l)}}}{\mathbf{h}_k^H \mathbf{R}^{-1}_{\mathbf{w},\mathbf{w}} \mathbf{h}_k}\,, \tag{5}$$

with $\hat{\mathbf{r}}_{\mathbf{x},m_k^{(l)}}$ given in (4). Since both $\mathbf{R}_{\mathbf{w},\mathbf{w}}$ and $\mathbf{h}_k$ are unknown, we replace them by their ML estimates. Using the known reference amplitude a_{ref}, we obtain $\hat{\mathbf{h}}_k = \frac{1}{a_{\mathrm{ref}} L_m} \hat{\mathbf{r}}_{\mathbf{x},m_k^{(1)}}$, while an estimate $\hat{\mathbf{R}}_{\mathbf{w},\mathbf{w}}$ of $\mathbf{R}_{\mathbf{w},\mathbf{w}}$ is computed as in (3) with $\mathbf{x}(n)$ replaced by $\hat{\mathbf{w}}(n) = \mathbf{x}(n) - \frac{1}{L_m} \hat{\mathbf{r}}_{\mathbf{x},m_k^{(l)}} m_k^{(l)}(n)$. Inserting these estimates into (5), we obtain the final amplitude estimate

$$\hat{a}_k^{(l)} \,=\, a_{\mathrm{ref}}\, \frac{\hat{\mathbf{r}}^H_{\mathbf{x},m_k^{(1)}} \hat{\mathbf{R}}^{-1}_{\mathbf{w},\mathbf{w}} \hat{\mathbf{r}}_{\mathbf{x},m_k^{(l)}}}{\hat{\mathbf{r}}^H_{\mathbf{x},m_k^{(1)}} \hat{\mathbf{R}}^{-1}_{\mathbf{w},\mathbf{w}} \hat{\mathbf{r}}_{\mathbf{x},m_k^{(1)}}}\,. \tag{6}$$

In practice, the assumptions mentioned above will be satisfied only approximately, but nevertheless we observed that (6) yields useful amplitude estimates.

Finally, using the detected midamble index set $\hat{\mathscr{L}}_k$ and the amplitude estimates $\hat{a}_k^{(l)}$, an estimate of the total midamble of the kth BS (see (2)) is obtained as

$$\hat{m}_k(n) \,=\, a_{\mathrm{ref}}\, m_k^{(1)}(n) + \sum_{l \in \hat{\mathscr{L}}_k} \hat{a}_k^{(l)} m_k^{(l)}(n)\,. \tag{7}$$

B. Channel Estimation

For simplicity, we will estimate the channels associated to different antenna elements separately. (This is theoretically optimal if the fading for different antenna elements is uncorrelated, which corresponds to a worst-case situation regarding channel estimation performance.) On the other hand, it is advantageous to jointly estimate all BS channels in a multiuser fashion. Let us partition the channel matrix $\mathbf{H}_k$ in (1) as

$$\mathbf{H}_k = \begin{bmatrix} \mathbf{g}_{k,1}^T \\ \vdots \\ \mathbf{g}_{k,M}^T \end{bmatrix}, \qquad (8)$$

where the $L \times 1$ vector $\mathbf{g}_{k,i}$ contains the L taps of the channel impulse response corresponding to the kth BS and the ith antenna element. The multiuser (all k) input-output relation for the ith antenna element can then be formulated as

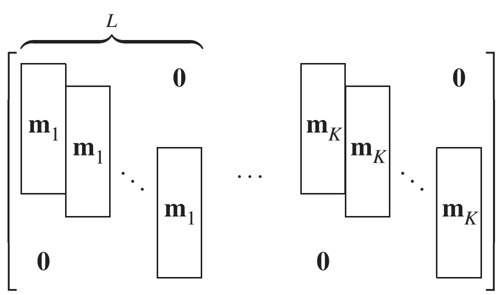
$$\mathbf{x}_i = \mathbf{C}\mathbf{h}_i + \mathbf{n}_i . \qquad (9)$$

Here, $\mathbf{x}_i \triangleq \big[x_i(1) \dots x_i(L_\mathrm{m} + L - 1)\big]^T$ is the signal received at the ith antenna element; the $LK \times 1$ vector

$$\mathbf{h}_i \triangleq \big[\mathbf{g}_{1,i}^T \, \dots \, \mathbf{g}_{K,i}^T\big]^T \qquad (10)$$

contains the channel impulse responses of all K BSs; $\mathbf{n}_i$ is a white Gaussian noise vector; and the $(L_\mathrm{m} + L - 1) \times LK$ midamble matrix $\mathbf{C}$ is defined as

$\mathbf{C} \triangleq$



with $\mathbf{m}_k \triangleq \big[m_k(1) \dots m_k(L_\mathrm{m})\big]^T$ denoting the total midamble vector of the kth BS (cf. (2)).

Assuming the channel vector $\mathbf{h}_i$ in (9) to be Gaussian, its MMSE estimate is [5]

$$\hat{\mathbf{h}}_{i,\mathrm{MMSE}} = \big(\mathbf{C}^H\mathbf{C} + \sigma^2\mathbf{R}_\mathbf{h}^{-1}\big)^{-1}\mathbf{C}^H\mathbf{x}_i , \qquad (11)$$

where $\mathbf{R}_\mathbf{h}$ denotes the covariance matrix of the channel impulse response $\mathbf{h}_i$ (in practice, $\mathbf{R}_\mathbf{h}$ does not depend on the antenna index i) and σ^2 is the noise variance. Note that via (8) and (10) we can convert the vectors $\hat{\mathbf{h}}_{i,\mathrm{MMSE}}$ into MMSE estimates $\hat{\mathbf{H}}_{k,\mathrm{MMSE}}$ of the channel matrices $\mathbf{H}_k$ in (1).

Whereas an estimate $\hat{\mathbf{C}}$ of the midamble matrix $\mathbf{C}$ is provided by the preceding midamble estimation stage, $\mathbf{R}_\mathbf{h}$ and σ^2 are unknown. Therefore, we first calculate the least-squares (LS) channel estimate [5]

$$\hat{\mathbf{h}}_{i,\mathrm{LS}} = (\mathbf{C}^H\mathbf{C})^{-1}\mathbf{C}^H\mathbf{x}_i ,$$

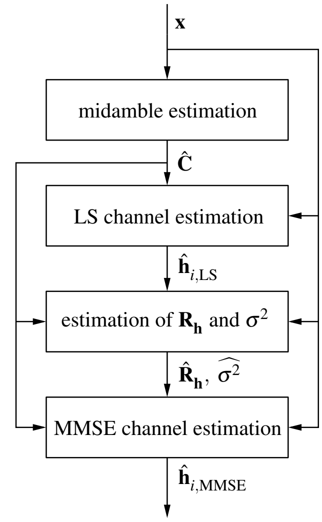


Fig. 4. Block diagram of the MMSE channel estimator.

which does not require knowledge of $\mathbf{R}_\mathbf{h}$ and σ^2. If the second-order statistics of the channel do not change over time, we can use the LS channel estimates $\hat{\mathbf{h}}_{i,\mathrm{LS}}$ of several successive frames to estimate $\mathbf{R}_\mathbf{h}$. Under the uncorrelated scattering assumption [6], the elements of $\mathbf{h}_i$ (i.e., the channel taps) are uncorrelated. Thus, an estimate of $\mathbf{R}_\mathbf{h}$ is given by the diagonal matrix $\hat{\mathbf{R}}_\mathbf{h} = \mathrm{diag}\big\{\widehat{\sigma_h^2}(1), \dots, \widehat{\sigma_h^2}(LK)\big\}$, where $\widehat{\sigma_h^2}(j)$ is the sample variance of the jth element of $\hat{\mathbf{h}}_{i,\mathrm{LS}}$ computed over the M antenna elements and over several successive frames. Furthermore, an estimate $\widehat{\sigma^2}$ of the noise variance σ^2 is obtained as the sample variance computed from all elements of the noise vector estimate $\hat{\mathbf{n}}_i = \mathbf{x}_i - \hat{\mathbf{C}}\hat{\mathbf{h}}_{i,\mathrm{LS}}$, again using averaging over all antenna elements and several successive frames. With $\hat{\mathbf{R}}_\mathbf{h}$ and $\widehat{\sigma^2}$, we can finally compute the MMSE channel estimate $\hat{\mathbf{h}}_{i,\mathrm{MMSE}}$ in (11). The overall procedure is depicted in Fig. 4.

Tables I and II show simulation results obtained with the LS and MMSE channel estimators for $M = 5$ antenna elements and two different simulation setups that are described in Section IV. As a performance measure, we use the normalized mean-square error (MSE) of the estimated channel impulse response matrices $\hat{\mathbf{H}}_{k,\mathrm{MMSE}}$ for different BSs. The signal-to-interference-and-noise ratio (SINR) of the various BSs is given in the first column of the tables. The MSE is estimated by averaging over 100 simulation runs consisting of 4 frames each. It is seen that, as expected, the MMSE estimator (using the LS estimator for estimating the channel statistics as explained above) performs better than the LS estimator. The MMSE estimates are seen to be reasonably accurate for stronger BSs; however, they are quite inaccurate for the weaker BSs because of the interference caused by the midambles of stronger BSs.

III. The SC-MMSE Channel Estimator

To improve the performance of the MMSE estimator for the weaker BSs, we propose to recursively apply the MMSE es-

TABLE I

Normalized MSE in dB obtained with the LS and MMSE channel estimators for the indoor environment, scenario 1.

Algorithm	LS		MMSE	
Channel	A	B	A	B
BS 1: −1.7 dB	−8.4093	−4.2369	−15.8688	−10.8329
BS 2: −9.7 dB	1.3099	4.6262	−8.6896	−4.2794
BS 3: −9.7 dB	0.5211	6.0579	−7.9954	−4.9862
BS 4: −14.7 dB	6.9336	11.4885	−4.0379	0.1691
BS 5: −14.7 dB	7.6124	12.7549	−2.8473	0.4117
BS 6: −17.7 dB	10.1995	17.2263	−1.0898	3.2672
BS 7: −17.7 dB	13.0418	17.1872	−1.0418	3.7462
BS 8: −17.7 dB	8.8302	14.8200	−2.4765	1.9762

TABLE II

Normalized MSE in dB obtained with the LS and MMSE channel estimators for the outdoor environment, scenario 1.

Algorithm	LS		MMSE	
Channel	A	B	A	B
BS 1: −1 dB	−10.0323	−1.9223	−16.8083	−7.0406
BS 2: −11 dB	3.3757	13.1206	−7.0478	1.8695
BS 3: −11 dB	1.5542	14.1872	−7.9517	2.0803
BS 4: −18 dB	11.7151	23.9497	−0.0339	10.4024
BS 5: −18 dB	11.5737	24.9874	−1.3372	10.3115
BS 6: −22 dB	19.3211	28.8500	5.2059	13.1688
BS 7: −22 dB	16.2978	28.2538	4.1985	14.1225
BS 8: −22 dB	17.2613	27.6705	3.4805	12.0914

timator within a successive interference cancellation scheme. This results in the novel *successive cancellation MMSE (SC-MMSE) estimator* that is depicted in Fig. 5. Using the MMSE channel estimates, the SC-MMSE algorithm reconstructs the component of the received signal corresponding to the midamble part of the strongest BS and subtracts it from the overall received signal. This interference cancellation step results in a significant increase of the SINR of the weaker BSs and, thus, in improved channel estimation performance.

More specifically, we start by estimating the midambles of all K BSs according to (7) and forming the corresponding estimate of the midamble matrix $\mathbf{C}$. We then calculate all M MMSE channel estimates $\hat{\mathbf{h}}_{i,\mathrm{MMSE}}$ as explained in Section II. From these vectors, we construct the channel matrix $\hat{\mathbf{H}}_{k,\mathrm{MMSE}}$ with k the index of the strongest BS. The channel estimates of the other BSs are discarded. We then reconstruct the midamble part of the signal corresponding to the strongest BS:

$$\hat{\mathbf{x}}_k(n) = \hat{\mathbf{H}}_{k,\mathrm{MMSE}}\,\hat{\mathbf{m}}_k(n)\,,$$

where $\hat{\mathbf{m}}_k(n) \triangleq \big[\hat{m}_k(n)\;\hat{m}_k(n-1)\;\ldots\;\hat{m}_k(n-L+1)\big]^T$. Finally, we subtract $\hat{\mathbf{x}}_k(n)$ from the received signal $\mathbf{x}(n)$.

In the next stage, the procedure is repeated with $\mathbf{x}(n)$ replaced by $\mathbf{x}(n)-\hat{\mathbf{x}}_k(n)$. The result is an MMSE estimate of the channel matrix of the second strongest BS, which is more accurate than the corresponding estimate obtained (but discarded) in the first stage. This estimation-cancellation recursion continues until all channel matrix estimates have been obtained.

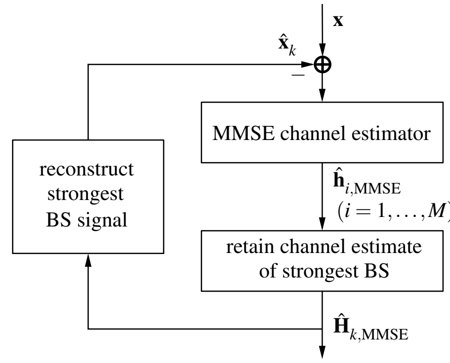


Fig. 5. Block diagram of the SC-MMSE channel estimator incorporating the complete MMSE channel estimator shown in Fig. 4.

IV. Simulation Results

Simulation setup. We used Clarke's channel model [7] according to which the channel weight vector associated to the kth BS and the pth path ($p=0,\ldots,L-1$; cf. (1)) is given as

$$\mathbf{h}_{k,p}(n) = \sum_{q=1}^{N_p^{(k)}} c_{p,q}^{(k)}\,\exp\big\{j\big(2\pi\nu_{p,q}^{(k)}n+\varphi_{p,q}^{(k)}\big)\big\}\,\mathbf{s}_{p,q}^{(k)}\,. \qquad (12)$$

Here, $N_p^{(k)}$ is the number of subpaths associated to the pth propagation path, and $c_{p,q}^{(k)}$, $\nu_{p,q}^{(k)}$, $\varphi_{p,q}^{(k)}$, and $\mathbf{s}_{p,q}^{(k)}$ are respectively the amplitude factor, normalized Doppler frequency, phase, and steering vector of the qth subpath of the pth path. The parameters $\nu_{p,q}^{(k)}$, $\varphi_{p,q}^{(k)}$, and $\mathbf{s}_{p,q}^{(k)}$ were randomly chosen such that a Rayleigh fading channel was obtained. Note that $\mathbf{h}_{k,p}(n)$ in (12) is time-varying (reflecting the movement of the mobile) whereas in (1) we assumed a channel that is constant within the midamble block. The loss in estimation performance caused by the channel's time variation will be small as long as the mobile does not move too fast.

We considered two different propagation environments, called "outdoor" and "indoor," that differ by their cell radius and channel parameters. For each environment, we defined two scenarios as illustrated in Fig. 6. In outdoor scenario 1, the receiver is located within the inner cell of a grid of 8 hexagonal cells. We will thus encounter one dominant BS signal and 7 weaker BS signals. In outdoor scenario 2, the receiver is located at the border of 3 cells, so that there impinge 3 equally strong BS signals and 6 weaker BS signals. (This is a challenging situation because the SC-MMSE channel estimator subtracts only one signal at a time and the other two dominant signals act as a strong interference.) Indoor scenario 1 has the same cell layout as outdoor scenario 1 but the cell radius is smaller. For indoor scenario 2, cells 1 and 2 are located above and below the other cells, respectively (corresponding to buildings with several floors), with the distances chosen such that we again have 3 equally strong BS signals.

In addition, we used two different channel parameter settings called A and B for each environment and scenario. For the out-

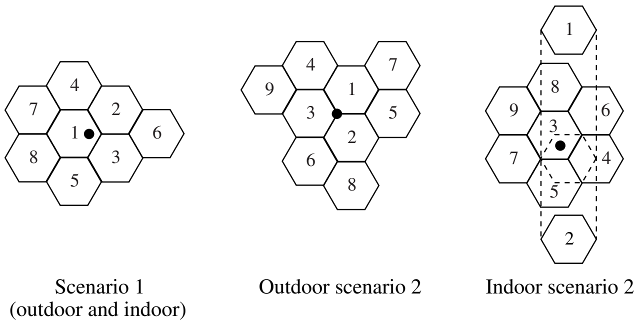


Fig. 6. Simulation scenarios. The bullet • indicates the receiver position.

door environment, channel A has 3 taps with a maximum delay of only 2 chips, whereas channel B has 8 taps with a maximum delay of 15 chips. For the indoor environment, channel A still has 3 taps with a maximum delay of 2 chips, but channel B now has 4 taps with a maximum delay of 3 chips.

Results of SC-MMSE channel estimation. Tables III and IV show the normalized MSE obtained with the SC-MMSE channel estimator for scenario 1 and 2, respectively. Both the indoor and outdoor environments are considered. The velocity of the mobile was set to 5 km/h, which is realistic for the measurement application considered. We averaged over 100 simulation runs consisting of 4 frames each. The maximum channel length L was set to 5 chips. This is sufficient for both indoor channels and for outdoor channel A. For outdoor channel B, however, the true channel length exceeds L, which results in a systematic channel estimation error.

It is seen that for the indoor environment, the SC-MMSE estimator performs very well. Accurate channel estimation can be achieved down to an SINR of about −18 dB for channel A and −15 dB for channel B. The performance for the challenging scenario 2 is not significantly poorer than for scenario 1, which shows that the SC-MMSE algorithm is robust to strong interference. This robustness is due to the use of multiuser channel estimation in every stage of the successive interference cancellation scheme. Thus, the influence of interference on the channel estimates is mitigated and the error that is passed on to the next stage via the subtraction process is kept small.

For the outdoor environment, the results for channel A are poorer than for the indoor environment, but nevertheless good accuracy is obtained down to about −17 dB. For channel B, the performance is quite poor in general. This is due to the large number of channel taps to be estimated and, in the outdoor case, also to the insufficient channel length L. Similarly to the indoor environment, the performance for scenario 2 is poorer than for scenario 1; again, this degradation is quite small.

TABLE III

Normalized MSE in dB obtained with the SC-MMSE channel estimator for scenario 1.

Environment	Indoor		Environment	Outdoor	
Channel	A	B	Channel	A	B
BS 1: −1.7 dB	−15.86	−10.83	BS 1: −1 dB	−16.80	−7.04
BS 2: −9.7 dB	−10.03	−6.15	BS 2: −11 dB	−10.28	0.73
BS 3: −9.7 dB	−12.08	−9.64	BS 3: −11 dB	−11.75	−0.88
BS 4: −14.7 dB	−9.77	−7.89	BS 4: −18 dB	−3.99	6.06
BS 5: −14.7 dB	−9.75	−7.64	BS 5: −18 dB	−7.57	4.53
BS 6: −17.7 dB	−8.44	−6.65	BS 6: −22 dB	−2.49	8.87
BS 7: −17.7 dB	−6.81	−5.04	BS 7: −22 dB	−2.14	11.61
BS 8: −17.7 dB	−9.06	−5.41	BS 8: −22 dB	−4.23	6.65

TABLE IV

Normalized MSE in dB obtained with the SC-MMSE channel estimator for scenario 2.

Environment	Indoor		Environment	Outdoor	
Channel	A	B	Channel	A	B
BS 1: −6.1 dB	−11.49	−8.00	BS 1: −5.1 dB	−13.33	−3.75
BS 2: −6.1 dB	−10.80	−7.85	BS 2: −5.1 dB	−15.17	−3.65
BS 3: −6.1 dB	−13.43	−9.92	BS 3: −5.1 dB	−15.77	−4.93
BS 4: −10.1 dB	−11.04	−8.37	BS 4: −17.1 dB	−3.30	5.15
BS 5: −10.1 dB	−11.80	−8.65	BS 5: −17.1 dB	−4.42	5.63
BS 6: −17.1 dB	−7.98	−5.84	BS 6: −17.1 dB	−5.79	2.44
BS 7: −17.1 dB	−7.31	−4.66	BS 7: −22.1 dB	−0.87	10.35
BS 8: −20.1 dB	−6.43	−4.79	BS 8: −22.1 dB	−1.72	8.70
BS 9: −20.1 dB	−4.52	−3.67	BS 9: −22.1 dB	−1.28	9.36

V. Conclusion

We presented a space-time algorithm for channel estimation in the downlink of a UMTS/TDD system. The proposed *successive cancellation MMSE (SC-MMSE) estimator* is a combination of an MMSE estimator with a successive interference cancellation scheme. It employs a GLRT technique for detecting the midambles present, an ML estimator for the midamble amplitudes, and estimation of the channel and noise statistics based on an LS channel estimate. Simulation results showed that the SC-MMSE estimator allows accurate channel estimation down to an SINR of about −17 dB for realistic propagation and interference scenarios.

Acknowledgments

The authors would like to thank P. Loubaton and J.-M. Chaufray (Université de Marne-la-Vallée) for numerous helpful suggestions and discussions.

References

[1] K. Kopsa, G. Matz, H. Artés, and F. Hlawatsch, "Space-time synchronisation algorithms for UMTS/TDD systems with strong co-channel interference," in *Proc. IEEE Globecom 2002*, Taipeh, Taiwan, Nov. 2002, pp. 254–258.

[2] 3GPP, "TS 25.221 Physical channels and mapping of transport channels onto physical channels (TDD)," www.3gpp.org, TS 25.221 v. 4.0.0, March 2001.

[3] 3GPP, "TS 25.223 Spreading and modulation (TDD)," www.3gpp.org, TS 25.223 v. 4.0.0, March 2001.

[4] Stephen M. Kay, *Fundamentals of Statistical Signal Processing: Detection Theory*, Prentice Hall, Upper Saddle River (NJ), 1998.

[5] Louis L. Scharf, *Statistical Signal Processing*, Addison Wesley, Reading (MA), 1991.

[6] P. A. Bello, "Characterization of randomly time-variant linear channels," *IEEE Trans. Comm. Syst.*, vol. 11, pp. 360–393, 1963.

[7] R. H. Clarke, "A statistical theory of radiomobile reception," *Bell Syst. Tech. J.*, vol. 47, pp. 957–1000, 1968.