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On the Optimality of Metrics for Coarse Frame Synchronization in OFDM: A Comparison

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ABSTRACT — Commonly, a repetition preamble [1] is proposed as burst training sequence to allow frame- and carrier frequency synchronization in digital transmission over unknown, severely dispersive channels. In this paper the preamble is composed of one repeated data–carrying — and therefore random — Orthogonal Frequency Division Multiplexing (OFDM) symbol. The current literature suggests several metrics to detect repetition preambles for coarse frame synchronization purposes so that we want to provide a ranking of four different metrics proposed in [1], [9], [11], and [2] via a simulative assessment. Furthermore, a probability–based motivation for the metric from [1] is given.

I. INTRODUCTION

OFDM offers advantages in transmission over (severe) multipath channels. Hence, there is an increased interest in applying OFDM in high–rate mobile data transmission [10]. We mention wireless Asynchronous Transfer Mode (ATM) as one potential field of interest [8]. ATM is a packet–oriented transmission scheme and the mostly non–continuous traffic in wireless ATM scenarios requires burst synchronization schemes which allow reliable single–shot frame- and carrier frequency synchronization.

Various ideas are proposed in literature to approach the synchronization problem with different assumptions [3, 4]. Here, the focus is on the repetition preamble scheme introduced for OFDM in [5] and further investigated for frame synchronization in [11] and [12]. The OFDM symbol which is repeated to form the preamble shall be used to carry data, too. Hence, the preamble itself is — apart from the periodicity — random and only one half of the preamble samples represents actual training overhead.

The general principle of exploiting a cyclic training signal for frame synchronization and carrier frequency offset estimation was originally suggested for single–carrier transmission in [1]. Moderate memoryless non–linear channel distortions will have negligible effects on the synchronization performance.

The paper is organized as follows: After the description of the transmission model in Section II, the various burst synchronization criteria are introduced in Section III. Their respective performance is presented in Section IV by means of simulation results. Section V is dedicated to conclusions.

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II. TRANSMISSION MODEL

We consider an OFDM burst consisting of several regular OFDM symbols, each generated with a D–dimensional inverse discrete Fourier transform (IDFT). The modulation interval for the system is denoted by T, so that the Nyquist bandwidth of the entire multiplex transmit signal is $1/T$. Thus, the regular subcarrier spacing is $\Delta f_{\text{sub}} = \frac{1}{DT}$. The synchronization preamble precedes the burst and consists of two identical D_{s}–carrier OFDM symbols — the first of which starting at discrete–time position $k = 0$ (cf. Fig. 1a). We gain an additional degree of freedom by not necessarily choosing D_{s} equal to D, like it is the case in [5, 11]. This implies that the synchronization OFDM symbol can be chosen smaller ($D_{\text{s}} < D$) to reduce overhead. The first of these two identical OFDM symbols gets a cyclic prefix [10] (guard interval) of D_{g} samples located in time positions $k = -D_{\text{g}}$ through -1.

The transmitted (zero–mean) channel symbols (samples) obtained from the IDFT plus guard interval extension are denoted as s_k. Their average power is $\sigma_s^2 \overset{\text{def}}{=} \mathcal{E}\left\{|s_k|^2\right\} = E_s/T$, where E_s is the average energy per channel symbol.

The periodicity in the preamble is symbolized by the triangles in Fig. 1a. Regions with the same shape denote identical sample values. Note that because of symbol repetition the tail of the first OFDM symbol simultaneously represents the guard interval for the second, so that the overall preamble length is only $2D_{\text{s}} + D_{\text{g}}$. Consequently, the transmit samples at time positions k and $k+D_{\text{s}}$ are identical for $k \in \{-D_{\text{g}}, \ldots, D_{\text{s}}-1\}$.

In the simulation setup we assume the worst–case scenario that the — random–information carrying and therefore non–fixed — preamble is embedded in a continuous stream of random regular OFDM symbols with the same average power.

The transmit signal is convolved with the channel impulse response and this yields some noiseless received signal $\tilde{r}_{0k}$. As long as the duration of the channel impulse response is shorter than the guard interval, the cyclic sample repetition is preserved in the channel–distorted received signal. Exactly this periodicity property is exploited for frame- and frequency synchronization purposes in [1]. The frequency mismatch between transmitter and receiver oscillator is modelled in the baseband by the modulation of $\tilde{r}_{0k}$ with the carrier frequency offset Δf_{co}. This yields the noiseless received sample $\tilde{r}_k = \tilde{r}_{0k}\mathrm{e}^{+\mathrm{j}2\pi\Delta f_{\text{co}}kT} = \tilde{r}_{0k}\mathrm{e}^{+\mathrm{j}2\pi\frac{k}{D}\xi_f}$, where we introduced the normalized carrier frequency offset (NFO) $\xi_f \overset{\text{def}}{=} \frac{\Delta f_{\text{co}}}{\Delta f_{\text{sub}}}$.

Noise samples n_k are added and therefore the received sample is $r_k = \tilde{r}_k + n_k$. If not explicitely stated, we assume white Gaussian noise. The noise variance is $\sigma_n^2 \stackrel{\text{def}}{=} \mathcal{E}\left\{|n_k|^2\right\} = N_0/T$, where N_0 is the power spectral density of the white noise.
The statistically independent zero–mean complex coefficients of the channel impulse response are randomly generated such that they follow a given channel power delay profile. The channel coefficients are newly generated once per burst and remain static during the entire burst. Directly after generation they are appropriately scaled to ensure that the sum over the squared magnitudes of the actual channel coefficients is equal to 1. Hence, the average signal–to–noise power ratio (SNR) at the receiver input is $E_s/N_0 = \sigma_s^2/\sigma_n^2$.

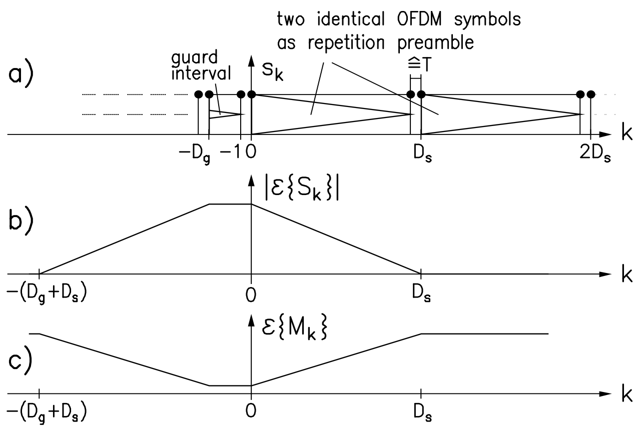

Figure 1: Symbolical illustration of the transmit signal during the repetition preamble. The expected values ($\mathcal{E}\{\cdot\}$) of the frame synchronization metrics M_k and S_k are depicted below for the special case of a non–dispersive channel.

III. BURST FRAME SYNCHRONIZATION

At least four different metrics are suggested in literature to achieve frame synchronization via detection of the repetition preamble. Here, they are altogether presented in a common notation to allow an easy structural comparison.

A. *Minimum Mean–Squared–Error Criterion*

To approach the problem of frame and frequency synchronization we collect a sequence of D_s contiguous noisy received samples in the vector $\boldsymbol{r}_k \stackrel{\text{def}}{=} (r_k, \ldots, r_{k+D_\text{s}-1})^\text{T}$. The (non–observable) noiseless received samples are collected in $\tilde{\boldsymbol{r}}_k \stackrel{\text{def}}{=} (\tilde{r}_k, \ldots, \tilde{r}_{k+D_s-1})^\text{T}$. Finally, with the definition of the noise vector $\boldsymbol{n}_k \stackrel{\text{def}}{=} (n_k, \ldots, n_{k+D_\text{s}-1})^\text{T}$ we have the relation $\boldsymbol{r}_k = \tilde{\boldsymbol{r}}_k + \boldsymbol{n}_k$.
The synchronization is based on maximizing the similarity probability of sample sequences. A valid time and frequency synchronization is achieved, if the synchronization tuple (k, ξ_f) is contained in the valid synchronization tuple set (region)

$$\mathcal{R}_{k,\xi_f} \stackrel{\text{def}}{=} \left\{ \left(k', \xi_f'\right) \,\middle|\, \tilde{\boldsymbol{r}}_{k'+D_\text{s}} = \text{e}^{+\text{j}2\pi\frac{D_\text{s}}{D}\xi_f'} \tilde{\boldsymbol{r}}_{k'} \right\}. \quad (1)$$

All time positions k' which exhibit the periodicity property, i.e., the identity between $\tilde{\boldsymbol{r}}_{k'+D_\text{s}}$ and $\text{e}^{+\text{j}2\pi\frac{D_\text{s}}{D}\xi_f'}\tilde{\boldsymbol{r}}_{k'}$, are valid. In the presence of an unconsumed guard interval the valid k' will form contiguous intervals. Apart from that the NFO ξ_f', is a valid estimate for all $\xi_f = \xi_f' + x\frac{D}{D_\text{s}}$ with $x \in \mathbb{Z}$, i.e., there is an NFO ambiguity interval of D/D_s. An unambiguous NFO estimate is a priori impossible, if the frequency parameter to be estimated is not restricted in range. Consequently, there exists a multiplicity of valid synchronization tuples, so that the cardinality of $\mathcal{R}_{k,\xi_f}$ is larger than one.
For periodicity detection we introduce the decision vector

$$\boldsymbol{d}_{\tilde{k},\tilde{\xi_f}} \stackrel{\text{def}}{=} \boldsymbol{r}_{\tilde{k}+D_\text{s}} - \text{e}^{+\text{j}2\pi\frac{D_\text{s}}{D}\tilde{\xi_f}} \boldsymbol{r}_{\tilde{k}} \quad (2)$$

$$= \underbrace{\tilde{\boldsymbol{r}}_{\tilde{k}+D_\text{s}} - \text{e}^{+\text{j}2\pi\frac{D_\text{s}}{D}\tilde{\xi_f}} \tilde{\boldsymbol{r}}_{\tilde{k}}}_{=0 \;\; \forall (\tilde{k},\tilde{\xi_f}) \in \mathcal{R}_{k,\xi_f}} + \boldsymbol{n}_{\tilde{k}+D_\text{s}} - \text{e}^{+\text{j}2\pi\frac{D_\text{s}}{D}\tilde{\xi_f}} \boldsymbol{n}_{\tilde{k}}, \quad (3)$$

which can be used to test the two synchronization hypotheses $\tilde{k}$ and $\tilde{\xi_f}$ simultaneously. It provides reasonable information at least for $\sigma_s^2 > \sigma_n^2$. In the case of valid hypotheses, $\boldsymbol{d}_{\tilde{k},\tilde{\xi_f}}$ represents a complex–valued zero–mean D_s–dimensional Gaussian distributed random variable. This property follows directly from Eq. (3). In the noiseless case $\boldsymbol{d}_{\tilde{k},\tilde{\xi_f}}$ will be exactly zero for the ideal frame positions and the perfect NFO estimates . The covariance matrix is $\mathbf{R} = \mathcal{E}\left\{\boldsymbol{d}_{\tilde{k},\tilde{\xi_f}} \boldsymbol{d}_{\tilde{k},\tilde{\xi_f}}^\text{H}\right\}$ and especially the mutual correlation of the two noise components $\boldsymbol{n}_{\tilde{k}+D_\text{s}}$ and $\boldsymbol{n}_{\tilde{k}}$ needs to be considered if the noise is not white. In the presence of mutually uncorrelated white Gaussian noise vectors $\boldsymbol{n}_{\tilde{k}+D_\text{s}}$ and $\boldsymbol{n}_{\tilde{k}}$, the noise in $\boldsymbol{d}_{\tilde{k},\tilde{\xi_f}}$ will again be white Gaussian with the covariance matrix $\mathbf{R} = 2\sigma_n^2 \cdot \mathbf{I}$, where $\mathbf{I}$ is the identity matrix.
The probability density function (pdf) of $\boldsymbol{d}_{\tilde{k},\tilde{\xi_f}}$ under the condition of a valid synchronization tuple is

$$p\left(\boldsymbol{d}_{\tilde{k},\tilde{\xi_f}} \,\middle|\, \left(\tilde{k}, \tilde{\xi_f}\right) \in \mathcal{R}_{k,\xi_f}\right) \sim \exp\left(-\boldsymbol{d}_{\tilde{k},\tilde{\xi_f}}^\text{H} \mathbf{R}^{-1} \boldsymbol{d}_{\tilde{k},\tilde{\xi_f}}\right), \quad (4)$$

where $(\cdot)^\text{H}$ denotes the (complex) conjugate transpose of a vector.
It is obvious that we have to estimate the frame offset and the NFO jointly. We obtain the joint estimates by performing

$$\left(\widehat{k}, \widehat{\xi_f}\right) = \underset{(\tilde{k},\tilde{\xi_f})}{\text{argmax}} \; p\left(\boldsymbol{d}_{\tilde{k},\tilde{\xi_f}} \,\middle|\, \left(\tilde{k}, \tilde{\xi_f}\right) \in \mathcal{R}_{k,\xi_f}\right). \quad (5)$$

The argmax–operator yields the argument (tuple) which maximizes the given expression.
This joint synchronization estimate is equivalent to

$$\left(\widehat{k}, \widehat{\xi_f}\right) = \underset{(\tilde{k},\tilde{\xi_f})}{\text{argmin}} \; \boldsymbol{d}_{\tilde{k},\tilde{\xi_f}}^\text{H} \mathbf{R}^{-1} \boldsymbol{d}_{\tilde{k},\tilde{\xi_f}}. \quad (6)$$

For white Gaussian noise the expression can be simplified to

$$\left(\widehat{k}, \widehat{\xi_f}\right) = \underset{(\tilde{k},\tilde{\xi_f})}{\text{argmin}} \; \|\, \boldsymbol{d}_{\tilde{k},\tilde{\xi_f}} \,\|^2, \quad (7)$$

where $\| \boldsymbol{d} \|^2 = \boldsymbol{d}^{\mathrm{H}}\boldsymbol{d}$. Applying Eq. (2) we perform the following modification

$$\begin{aligned} \| \boldsymbol{d}_{\tilde{k},\tilde{\xi}_f} \|^2 &= \| \boldsymbol{r}_{\tilde{k}+D_{\mathrm{s}}} - \mathrm{e}^{+\mathrm{j}2\pi\frac{D_{\mathrm{s}}}{D}\tilde{\xi}_f}\boldsymbol{r}_{\tilde{k}} \|^2 \\ &= \|\boldsymbol{r}_{\tilde{k}+D_{\mathrm{s}}}\|^2 + \|\boldsymbol{r}_{\tilde{k}}\|^2 - 2\Re\left\{\mathrm{e}^{-\mathrm{j}2\pi\frac{D_{\mathrm{s}}}{D}\tilde{\xi}_f}\boldsymbol{r}_{\tilde{k}}^{\mathrm{H}}\boldsymbol{r}_{\tilde{k}+D_{\mathrm{s}}}\right\} \\ &= P_{\tilde{k}+D_{\mathrm{s}}} + P_{\tilde{k}} - 2\Re\left\{\mathrm{e}^{-\mathrm{j}2\pi\frac{D_{\mathrm{s}}}{D}\tilde{\xi}_f}S_{\tilde{k}}\right\}, \end{aligned} \tag{8}$$

where we introduced the complex correlation

$$S_k \overset{\mathrm{def}}{=} \boldsymbol{r}_k^{\mathrm{H}}\boldsymbol{r}_{k+D_{\mathrm{s}}} \tag{9}$$

and the power sum inside a frame of D_{s} subsequently received samples

$$P_k \overset{\mathrm{def}}{=} \| \boldsymbol{r}_k \|^2 . \tag{10}$$

Both values, S_k and P_k, can be recursively calculated from S_{k-1} and P_{k-1}, respectively.

The expression in Eq. (7) is exactly the same metric which Chevillat, Maiwald and Ungerboeck proposed in [1] as periodicity metric for joint frame- and frequency synchronization. It is a norm for the mean–squared error (MSE) between the received samples, spaced D_{s} samples apart and can therefore be exploited to monitor the degree of periodicity in a signal corrupted by white Gaussian noise. The joint estimate obtained from the two–dimensional metric in Eq. (7) is in favour of the frame start hypothesis $\tilde{k}$ and the NFO hypothesis $\tilde{\xi}_f$ which achieve the minimum MSE (MMSE).

With the modified metric

$$M_{\tilde{k}} \overset{\mathrm{def}}{=} P_{\tilde{k}+D_{\mathrm{s}}} + P_{\tilde{k}} - 2\left|S_{\tilde{k}}\right| \tag{11}$$

the original two–dimensional search can be broken down into two one–dimensional estimation problems [1]. The estimation of the frame position comes first via the MMSE criterion

$$\widehat{k} = \underset{\tilde{k}}{\operatorname{argmin}}\ M_{\tilde{k}}. \tag{12}$$

Thereafter the maximum–likelihood (ML) estimate [13] for the NFO can be obtained by evaluating S_k at the estimated frame start, i.e., $k = \widehat{k}$, and this yields $\widehat{\xi}_f = \frac{D}{2\pi D_{\mathrm{s}}}\arg\left(S_{\widehat{k}}\right)$. Clearly, $|\xi_f| < D/(2D_{\mathrm{s}})$ is a minimum requirement for the non–ambiguity of the frequency offset estimate $\widehat{\xi}_f$.

For SNRs larger than 1 in a non–dispersive channel the mean value of M_k will exhibit a constant–valued minimum within the guard interval region $-D_{\mathrm{g}} \le k \le 0$ (cf. Fig. 1c). A similar "flat peak" behaviour will occur in the synchronizer for (partly) unconsumed guard intervals, i.e., when the channel impulse response is shorter than the scheduled cyclic extension.

B. *Maximum–Likelihood Criterion*

In [9] Sandell, van de Beek and Börjesson propose an optimum metric which is based on a ML frame synchronization approach. The detailed derivation can be found in [13]. The received signal is modelled as a complex zero–mean Gaussian distributed white random process. The zero–correlation of samples is not generally true for OFDM transmit signals with strongly varying transmit powers in the subcarriers as it is the case with large numbers of unused subcarriers [6] or with adaptive modulation. It is especially not true for any received signal if it was convolved with some dispersive channel impulse response. Consequently, the derivation in [13] is mainly based on the assumption of a non–dispersive channel and uncorrelated additive noise. With the same reasoning as in the previous subsection they finally arrive at the search criterion

$$\widehat{k} = \underset{\tilde{k}}{\operatorname{argmin}}\ \left(\rho\left(P_{\tilde{k}+D_{\mathrm{s}}} + P_{\tilde{k}}\right) - 2\left|S_{\tilde{k}}\right|\right) \tag{13}$$

for frame synchronization, where the constant $\rho \overset{\mathrm{def}}{=} \frac{\sigma_s^2}{\sigma_s^2+\sigma_n^2}$ accounts for the SNR at the receiver input. Apart from this SNR–adaptive factor the metric has the same structure as the one in Eq. (11). We will see from the simulation results in Section IV that the latter metric retains its superiority in dispersive channels.

C. *Maximum–Correlation Criterion*

A simplified frame synchronization metric is proposed by Keller and Hanzo in [2]. Here, we obtain the frame start via [2]

$$\widehat{k} = \underset{\tilde{k}}{\operatorname{argmax}}\ \left|S_{\tilde{k}}\right|, \tag{14}$$

which represents the time position of maximum correlation (MC) magnitude. Equivalently, the maximum of $\left|S_{\tilde{k}}\right|^2$ can be the criterion, so that no square roots need to be processed in an implementation.

If the received signal has a constant envelope and the noise is moderate so that $P_k = \mathrm{const}\ \forall k$, then the latter criterion would be comparable to the criteria in Eqs. (13) and (12). But this is definitely never true for OFDM signals as the signal envelope of OFDM is far from constant [6]. It is even not constant for multipath–corrupted receive signals in single–carrier modulated systems. Consequently, the criterion in Eq. (14) must be suboptimum, as it does not account for the average power inside the currently processed synchronization window.

See Fig. 1b) for the course of the expectation of this metric in a non–dispersive channel.

D. *A Fourth Criterion*

Schmidl and Cox suggest to apply the "defined" [11] metric

$$\widehat{k} = \underset{\tilde{k}}{\operatorname{argmax}}\ \left(\left|S_{\tilde{k}}\right|^2 / P_{\tilde{k}+D_{\mathrm{s}}}^2\right). \tag{15}$$

This metric lacks a theoretical motivation, and hence an assessment prior to simulation is impossible.

IV. SIMULATION RESULTS

For the simulation setup we used $D = D_{\mathrm{s}} = 64$ with 53 active (non–zero) subcarriers and a guard interval of $D_{\mathrm{g}} = 8$. For completeness we mention the type of modulation in the subcarriers, although it has negligible impact on the time–domain behaviour and therefore does not affect any one of the results given in this paper. We used 4DPSK in the synchronization symbol and 8DPSK in the regular OFDM symbols. The simulated "burst" consists of one repetition preamble composed of a repeated $D_s = 64$–carrier OFDM symbol plus guard interval. This preamble is surrounded by random $D = 64$–carrier OFDM symbols plus guard extension. We configured one such OFDM symbol on each side. Hence, the synchronizer searched for the frame start in an interval of $D_g + D + D_g = 80$ samples to the left and $D_g + D = 72$ samples to the right of the correct frame synchronization instant at $k = 0$.

We used a T–spaced discrete–time and exponentially decaying channel power delay profile of length 8, which decays with -3 dB per tap in positive time direction. This is often used to model an indoor radio communications channel.

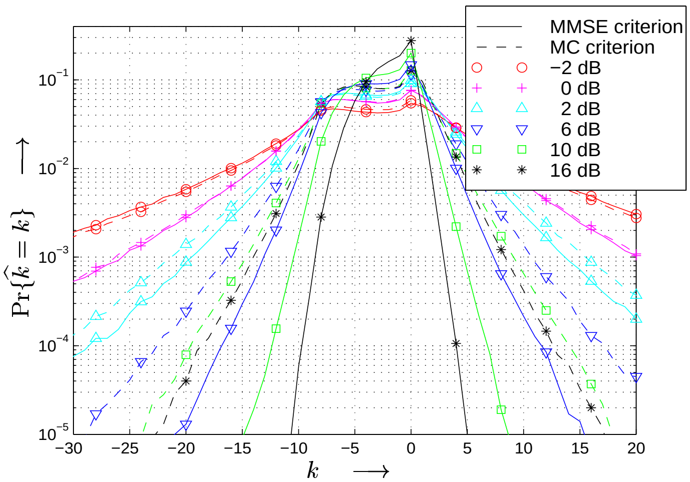

Figure 2: Simulation results for the lock–in probabilities in a dispersive channel. The simulations are performed for various $10\log_{10}(E_s/N_0)$ [dB] to compare the frame synchronization criteria in Eq. (12) and Eq. (14).

Simulation results of lock–in probabilities for the MMSE and MC frame synchronization criteria over the dispersive channel are given in Fig. 2 and we point out two observations:

1.) At high SNRs the MMSE criterion shows a distinctly superior lock–in performance over the MC criterion as the latter disregards the severely non–constant envelope of the OFDM signal. For SNRs lower than 1 ($\widehat{=}$0 dB), MC would be preferable.

2.) We find a surprising result in the guard interval region as the lock–in probabilities form a slight hollow in the middle. This effect is theoretically illuminated for non–dispersive channels in [7] and it is still visible in this moderate multipath channel.

This simulated histogram is very interesting, but it does not reveal the hit or miss probability of the coarse frame synchronizer. To have a norm for this, we introduce the timing failure (tf) probability

$$\mathrm{P}_{\mathrm{tf}}^{(m)} = \Pr\left\{\left|\widehat{k} - \mathcal{E}\left\{\widehat{k}\right\}\right| > m\right\}, \qquad (16)$$

which is the probability that the frame synchronizer misses an interval of $2m+1$ samples centered at the mean frame synchronization position $\mathcal{E}\left\{\widehat{k}\right\}$. Hence, $\mathrm{P}_{\mathrm{tf}}^{(m)}$ is a measure for the robustness of the coarse frame synchronization estimate.

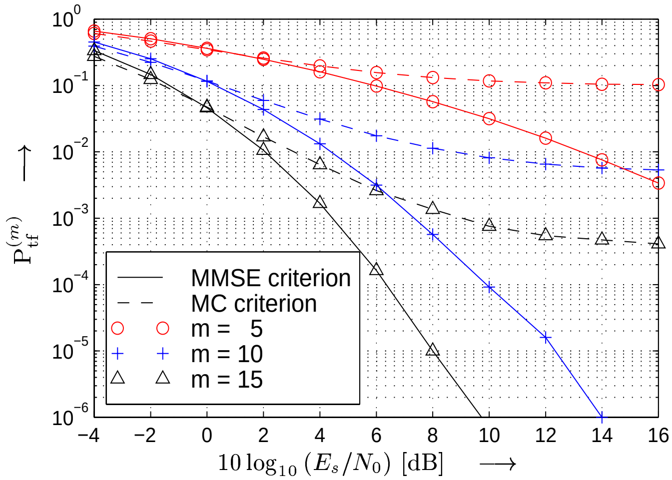

Figure 3: Simulated probabilities to miss a $\pm m$–interval. The frame synchronization criteria in Eq. (12) and Eq. (14) are compared in the dispersive channel.

In Fig. 3 we find the simulated $\mathrm{P}_{\mathrm{tf}}^{(m)}$ for the MMSE and MC frame synchronization criteria we already have seen in the lock–in histogram in Fig. 2. This diagram reveals a severe flattening effect of $\mathrm{P}_{\mathrm{tf}}^{(m)}$ at high SNRs, if the MC criterion is applied. This is caused by ignoring the power sum terms in the frame synchronization metric when migrating from the MMSE criterion in Eqs. (11) and (12) to the MC criterion in Eq. (14). The power sum terms are of viable importance in OFDM. Interestingly, we observe a cross–over point at $10\log_{10}(E_s/N_0) = 0$ dB, which means that the MC criterion would be preferable in applications at very low SNRs.

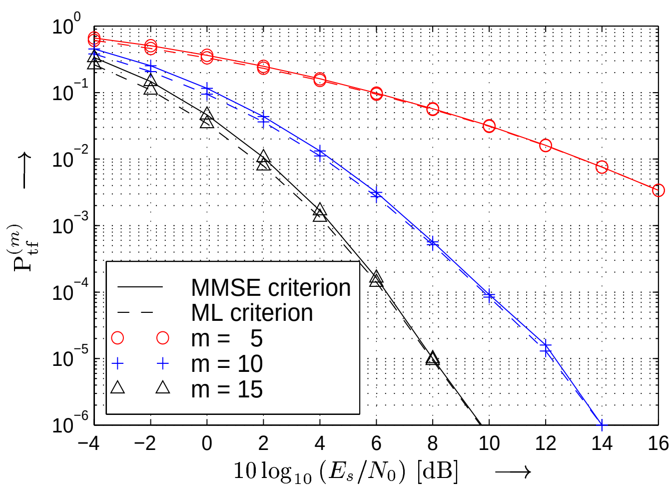

Figure 4: Simulated probabilities to miss a $\pm m$–interval. The frame synchronization criteria in Eq. (12) and Eq. (13) are compared in the dispersive channel.

In Fig. 4 we want to compare the MMSE criterion to the ML criterion. For the ML metric we assume perfect estimates of

σ_s^2 and σ_n^2 and therefore perfect knowledge of ρ. The most important observation is that both criterions become asymptotically identical at high SNRs. At 8 dB the performance difference becomes negligible. At very low SNRs we observe an advantage of 0.2 to 0.4 dB of the ML criterion over the MMSE criterion.

As observed in Fig. 2, the MC criterion performs better at low SNRs, while the MMSE criterion works fine at high SNRs. We can interpret the ML criterion in Eq. (13) as a weighted combination criterion, which gradually moves between MMSE ($\rho \to 1$ for high SNRs) and MC ($\rho \to 0$ for SNRs lower than 0 dB). Consequently, the ML criterion is a SNR–adaptive optimum mixture of MMSE and MC.

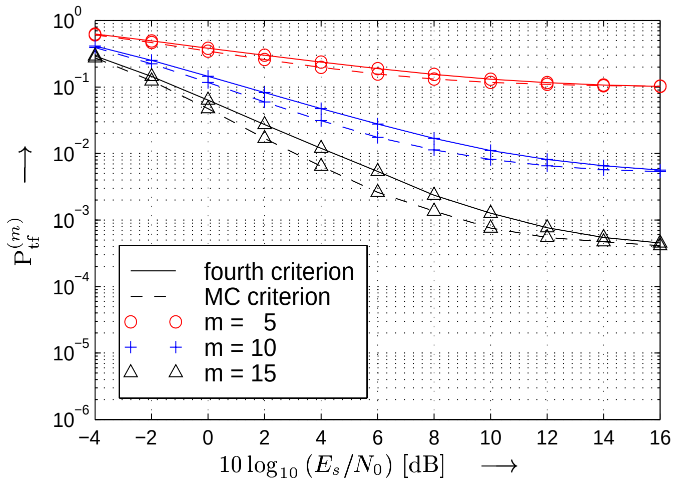

Figure 5: Simulated probabilities to miss a $\pm m$–interval. The frame synchronization criteria in Eq. (14) and Eq. (15) are compared in the dispersive channel.

For a last comparison we investigate the fourth proposed criterion for frame synchronization from Eq. (15). Its performance is depicted together with the performance of the MC criterion in Fig. 5. We find a very suboptimum lock–in performance which is even worse than the MC criterion alone.

V. SUMMARY AND CONCLUSIONS

A simulative assessment of the four different metrics proposed in [1], [9], [11], and [2] was provided in this paper. We found the latter two metrics to be suboptimum, while the ML metric in [9] performs best and — for moderate noise — is asymptotically identical with the slightly less complex MMSE metric in [1].

The repetition–preamble structure together with the MMSE criterion in Eq. (12) or the ML criterion in Eq. (14) allows a robust coarse frame synchronization which is suitable for reliable timing acquisition in unknown dispersive channels. Even though the MMSE criterion is slightly inferior to the ML criterion it will be preferred in applications with working points at rather high SNRs, as it does not require an SNR estimate prior to synchronization.

Clearly, the (best possible) frame synchronization performance depicted in Fig. 4 is not yet satisfying for such short ($D = 64$) OFDM symbols. Too much interference power is acquired by the rather frequent misalignments of the demodulation (DFT) window. Appropriate refinement algorithms must be implemented to allow a fine frame synchronization with improved accuracy. One possibility to achieve a significant improvement is the topic of current research to be published in near future.

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