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SIMPLIFICATION OF A LINK PERFORMANCE PREDICTION METHOD BASED ON MUTUAL INFORMATION

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Abstract: In this paper, we propose a method to predict the block error rate performance of the wireless links in OFDM communication systems. Our approach relies on a performance prediction methodology that uses the mean mutual information per coded bit as quality measure. We make a simplification within this methodology such that, contrary to existing approaches, our method needs the generation and storage of much less reference performance curves. Simulation results obtained for both additive white Gaussian noise and multipath fading channels demonstrate the very good prediction capability of the proposed method.

Keywords: *Link performance prediction, OFDM, block error rate, mutual information, MMIB.*

I. INTRODUCTION

Modern wireless communication systems are required to provide very high data rates and enhanced network capacity. To improve the system performance, advanced techniques have to be used on the radio interface to combat the impairments of the wireless medium, such as the channel variations in time and frequency. To that end, capacity approaching channel codes (e.g., turbo codes) and adaptive mechanisms such as fast link adaptation and channel dependent scheduling play an important role.

In this context, methods to predict the performance of wireless links – usually quantified by the block error rate (BLER) – are very much needed for the design of communication systems. A typical application is in system-level simulations where the overall system performance of a communication network is evaluated; at this level, identifying the performance of all radio links poses major complexity difficulties, since exhaustive link-level simulations of a large number of links are practically impossible due to computational power constraints. BLER prediction methods are also required for the design and operation of advanced adaptation mechanisms, because link adaptation and channel-dependent scheduling need feedback quality metrics that are strongly correlated with the actual performance of the radio link.

Link performance prediction has been an active area of research and has received considerable attention in scientific literature and standardization bodies [1-7]. Its purpose is to predict the block error rate (BLER) for a particular configuration of the transmission parameters (information block length, channel code parameters, code rate, modulation format) and for the instantaneous state of the fading channel. The general approach for the existing methods involves two steps: first, a compression step maps the set of instantaneous signal-to-noise ratios (SNRs) of the used resource elements to a scalar quality metric that should be highly correlated with the actual BLER of the link; then, during the performance mapping step, the link quality metric is mapped to a BLER value by using look-up tables or functions that contain the reference performance for additive white Gaussian noise (AWGN) channels.

A performance prediction method has to be accurate and computationally simple. As the accuracy is highly influenced by the link quality metric, several possible metrics are studied in the literature. Among them, the mostly used are the exponential effective-SNR mapping (EESM) method [2] and the mutual information (MI) based methods [4-7], due to their high prediction accuracy. MI metrics are proved to be also very effective in link adaptation mechanisms [8, 9]. We have also used MI metrics for BLER prediction [10] and link adaptation [11] in cooperative systems.

In general, a reference AWGN performance curve needs to be obtained through simulations and stored for each possible transmission configuration, i.e., information block length, code rate and modulation. An advantage of MI-based methods is that the decoding performance is modulation independent when expressed in the MI domain; therefore, the AWGN performance is only required for each code rate and info block length when MI metrics are used. However, this can still be an important issue, because the latest standards such as 3GPP LTE specify a lot of possible values for the information block length and code rate; this would require a lot of BLER mapping functions to be stored and made available for the second step of the prediction method.

In this paper, we study BLER prediction when using turbo coded OFDM transmissions on multipath fading channels. Due to the previously mentioned advantages of MI- based methods, we opt for the mean mutual information per coded bit (MMIB) quality metric [6]. Our main contribution is a simplification we make within the MMIB methodology such that, contrary to exiting approaches, the method we obtain is able to predict the decoding performance for any code rate based on the AWGN performance curve for a reference code rate (e.g., the mother rate of the turbo code) only. Therefore, for a given information block length, our proposed method requires that

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only the mapping function corresponding to the reference code rate needs to be available, regardless the code rate that is actually used. Even if our method is heuristically derived, simulation results prove its very good prediction capability.

The rest of the paper is structured as follows: Section II describes the considered OFDM wireless system; in Section III, we present some general aspects of link performance prediction, the MMIB method in brief and then our proposed simplification; Section IV contains validation results for our method, while Section V concludes the paper.

II. SYSTEM MODEL

We consider an OFDM wireless system where a sequence of information bits $\mathbf{u}\in\{0,1\}^K$ with length K has to be transmitted using frequency-time resources of N subcarriers and L OFDM symbols. First, the information bits are encoded with a turbo code with mother rate $R_0 = 1/3$. Then, a circular buffer rate matching algorithm [12] punctures the coded bits such that a code block $\mathbf{c}\in\{0,1\}^C$ with a desired length C is output and the resulting code rate is $R = K/C$. The coded bits in $\mathbf{c}$ are randomly interleaved and then mapped on symbols $\mathbf{x}$ belonging to a complex alphabet X with M bits per symbol and unitary power. The parameters are set such that $C \le MNL$. Finally, the symbols are OFDM modulated by performing an IFFT and inserting a cyclic prefix (CP), and the OFDM signal is transmitted through a multipath channel.

The received OFDM signal is demodulated by removing the CP and using an FFT. Under ideal conditions, the signal on the nth subcarrier of the lth OFDM symbol reads

$$y_{n,l} = h_{n,l}\,x_{n,l} + z_{n,l} \quad n = 1,\ldots,N,\ l = 1,\ldots,L. \tag{1}$$

In (1), $h_{n,l}$ denotes the sample of the channel frequency response, $x_{n,l}$ is the transmitted symbol and $z_{n,l}$ stands for the zero-mean AWGN with variance σ^2. The instantaneous SNR of the resource element with indices (n,l) is

$$\rho_{n,l} = \frac{\left|h_{n,l}\right|^2}{\sigma^2}. \tag{2}$$

We assume the receiver perfectly knows the channel weights $h_{n,l}$, for all $n = 1,\ldots,N$, $l = 1,\ldots,L$, and the noise power σ^2. The receiver performs soft demapping by computing the log-likelihood ratios (LLR) of the coded bits:

$$\lambda_{n,l}^{m} = \ln\frac{\sum_{s\in \mathrm{X}_m^1}\exp\left(-\sigma^{-2}\left|y_{n,l}-h_{n,l}s\right|^2\right)}{\sum_{s\in \mathrm{X}_m^0}\exp\left(-\sigma^{-2}\left|y_{n,l}-h_{n,l}s\right|^2\right)}$$

where $\lambda_{n,l}^{m}$ denotes the LLR of the coded bit $c_{n,l}^{m}$ mapped on the mth bit position of symbol $x_{n,l}$, $m = 1,\ldots,M$, and X_m^1 and X_m^0 are the subsets of the alphabet X containing those symbols whose mth bit value equals 1 and 0, respectively. The set of LLRs is fed to the turbo decoder which yields the decoded bits $\hat{\mathbf{u}}$; a block error occurs when $\hat{\mathbf{u}} \ne \mathbf{u}$.

III. LINK PERFORMANCE PREDICTION METHOD

The problem at hand is to obtain a method to predict the BLER of the transmissions in the system described in Section II. This would permit the prediction of the BLER attained with a specific configuration of the transmission parameters for the current channel state, without actually simulating the transmission chain.

When the transmission channel is only affected by AWGN, the link performance is usually quantified in terms of the block error rate as a function of the SNR $\rho = \sigma^{-2}$. This performance characterization is sufficient as long as the SNR is constant during the transmission of one code block. However, the AWGN channel model is not valid in OFDM-based systems because the wireless channel is time and frequency selective. Therefore, the SNR values (2) can be significantly different and the decoding performance strongly depends on the particular channel state. So, the challenge is to conceive an accurate and computationally simple method which is able to predict the BLER for a given transmission configuration (K, R, M) and for a particular channel realization, i.e., specific values of $h_{n,l}$.

We will make use of a BLER prediction method that uses the mean mutual information per coded bit (MMIB) metric, which was proven to be very accurate [6]. Moreover, we propose a simplification of this method such that it would need the generation and storage of much less reference AWGN performance curves.

A. Outline of the MMIB method

Similar to other performance prediction methods, the MMIB method [6] also consists of two steps, i.e., the compression step and the performance mapping step. In this subsection, we will briefly present these steps in our system model.

First, the SNR values $\rho_{n,l}$, $n = 1,\ldots,N$, $l = 1,\ldots,L$, are compressed to a scalar quality metric. With a mutual information quality model, the compression function makes use of the MMIB defined over the binary-input soft-output channel between the encoder and the decoder.

In general, assuming a modulation alphabet with M bits per symbol, the mutual information between a code bit c on the mth bit position of a modulation symbol and its corresponding LLR λ is given by [6]

$$I_M^m(\rho) = \frac{1}{2}\sum_{b\in\{0,1\}}\int_{-\infty}^{\infty} f_M^m(l\,|\,b)\log_2\left(\frac{2f_M^m(l\,|\,b)}{f_M^m(l\,|\,b=0)+f_M^m(l\,|\,b=1)}\right)\mathrm{d}l, \tag{3}$$

where ρ is the SNR and $f_M^m(l\,|\,b)$ is the probability density function of the LLR conditioned by the bit value on position m. The conditional PDFs depend on the SNR and on the modulation mapping. For high-order modulations ($M > 2$), the PDFs have different forms for different bit positions.

The values computed with (3) are averaged over the bit positions to obtain a symbol-averaged mutual information:

$$I_M(\rho) = \frac{1}{M}\sum_{m=1}^{M} I_M^m(\rho). \tag{4}$$

The main inconvenient is the lack of an analytical expression to compute (3) and, consequently, (4). As proposed in [6], (4) can be well approximated with parametric analytical functions whose parameters are determined through Monte Carlo simulations.

The link quality metric computed by the compression step is the mean mutual information per coded bit, i.e., the average value of (4) computed for all the resource elements that carry the code block. In our system model, the MMIB is

$$\bar{I} = \frac{1}{NL}\sum_{n=1}^{N}\sum_{l=1}^{L} I_M\left(\rho_{n,l}\right), \quad (5)$$

where $\rho_{n,l}$ is the instantaneous SNR given in (2). In short, the compression step basically involves the mapping from the SNR domain to the mutual information domain (5) for each transmitted resource element, and then the averaging of the obtained values with (5). The MMIB value characterizes the the quality of the LLR values at the decoder's input.

Finally, in the performance mapping step, a MMIB to BLER mapping function is used to predict the link performance. This mapping is based on BLER reference results previously obtained through link-level simulations on AWGN channels and depends on K and R. The BLER value returned by the mapping function should be very close to the value that would be obtained by simulations for the current state of the fading channel. Denoting the mapping function by $\Gamma_{K,R}(\cdot)$, we have $BLER_{\text{pred}} = \Gamma_{K,R}(\bar{I})$. In [6], it is proposed a simple way to represent the AWGN performance with a parametric function:

$$BLER_{\text{pred}} = \Gamma_{K,R}\left(\bar{I}\right) = \frac{1}{2}\left[1-\text{erf}\left(\frac{\bar{I}-\varphi_{K,R}}{\sqrt{2}\omega_{K,R}}\right)\right], \quad (6)$$

where $\bar{I}$ is the MMIB computed with (5), and $\varphi_{K,R}$ and $\omega_{K,R}$ are parameters depending on K and R, their values being determined through simulations and curve fitting.

B. The proposed simplification

In the previous section, we have shortly presented the steps of a BLER prediction method that uses the MMIB as a link quality measure. The SNR values $\rho_{n,l}$ are compressed to the MMIB value (5), which is then mapped by (6) to the predicted BLER value. Note that a mapping function (6) has to be available for each (K, R) pair that can be used in the system; this could be an important issue, because in modern standards, such as 3GPP LTE, a lot of possible values are specified for the information block length K and the code rate R. For example, in [12] 188 possible values for K are specified, while the circular buffer rate matching algorithm can output code blocks with almost any length such that the code rate R may take roughly any value between the mother code rate 1/3 and 1. Therefore, there would be a lot of (K, R) combinations and hence a very high number of mapping functions would be required.

To alleviate the complexity involved by generating and storing a great number of mapping functions, we propose a method to simplify the performance mapping mechanism. Our simplification relies on the following empirical observations related to the BLER performance in the mutual information domain:

- the MMIB distance between two BLER vs. MMIB curves obtained for the same K and two different code rates is approximately the same at all BLER values;
- for a given code rate R, the MMIB value required to achieve a particular BLER value can be approximated by the parametric function $\bar{I} \approx a_K R^2 + (\delta - a_K) R$, where a_K depends on K and on the particular value of BLER;
- the dependency of a_K on K can be approximated by $a_K \approx \alpha K^{\beta} + \gamma$.

Based on these observations, for a given K, we can predict the BLER value for any $R\in [1/3,1)$ using only one mapping function $\Gamma_{K,R_0}(\cdot)$, which is previously obtained for K and for a reference code rate that we choose to be the mother rate R_0. Specifically, for a transmission with given parameters K, M and R, the BLER that would be attained over a multipath fading channel can be accurately predicted by

$$BLER_{\text{pred}} \approx \Gamma_{K,R_0}\left(\bar{I}_0\right), \quad (7)$$

with

$$\bar{I}_0 = \bar{I} - \left(\alpha K^{\beta} + \gamma\right)\left(R^2 - R_0^2\right) - \left(\delta - \alpha K^{\beta} - \gamma\right)\left(R - R_0\right), \quad (8)$$

where $\bar{I}$ is given by (5). In this way, regardless the actual value of R, only the mapping functions $\Gamma_{K,R_0}(\cdot)$ corresponding to the set of K values employed in the system and the mother rate $R_0 = 1/3$ need to be generated and stored.

IV. SIMULATION RESULTS

In this section, we validate our proposed simplified BLER prediction method through computer simulations. We consider the OFDM system described in Section II with subcarrier separation Δf = 15 kHz, L = 7 OFDM symbols, while the number of subcarriers N is an integer multiple of 12 and depends on the code block length. We use the convolutional turbo code specified in [12], a QPSK modulation (M = 2) and the ITU Pedestrian B multipath channel model. For the considered turbo code, the parameters in (8) are found to be: α = -1.428, β = -0.31, γ = -0.212 and δ = 1.012.

First, we prove the accuracy of the approximation in (7) by performing simulations on AWGN channels. The accuracy of our method is proved in Fig. 1 for a fixed value of K and for several values of $R\in [1/3,1)$, and in Fig. 2 for $R\in \{0.5,0.8\}$ and K$\in$ {144, 432, 864, 2304}. The results show that the predicted BLER curves ($BLER_{\text{pred}}$) computed with (7) are very close to the BLER values obtained through simulations ($BLER_{\text{sim}}$).

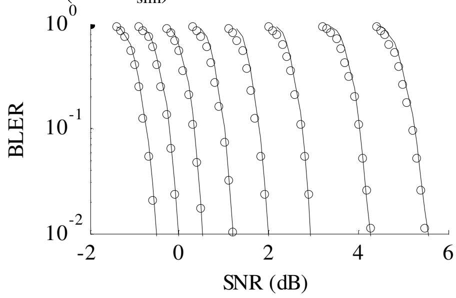

Figure 1. $BLER_{\text{pred}}$ (continuous lines) and $BLER_{\text{sim}}$ (circles); AWGN channel, K = 1152 bits and R is varied.

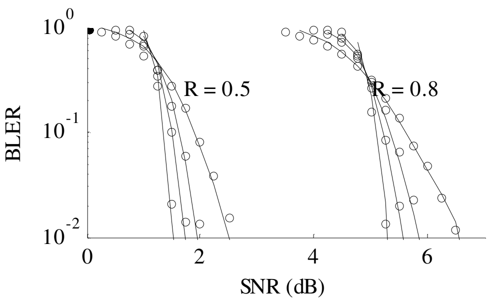

Figure 2. $BLER_{\text{pred}}$ (continuous lines) and $BLER_{\text{sim}}$ (circles); AWGN channel, $R \in \{0.5, 0.8\}$ and K is varied.

Next, we validate our BLER prediction method for OFDM transmissions over the multipath fading channel and a moving speed of 3 km/h. Due to the assumed channel model, the channel weights vary across the occupied time-frequency resources, such that the SNRs (2) are significantly different. However, with a MMIB quality metric, we can see in Fig. 3 that that the simulated BLER points at different code rates fall on top of the prediction curves given by (7), showing the high accuracy of our method. A $BLER_{\text{sim}}$ point is obtained by performing simulations for a fixed set of channel weights generated according to the channel model; the multiple points that fall on a $BLER_{\text{pred}}$ curve correspond to a particular code rate and are obtained for various sets of channel weights and/or noise powers. Fig. 4 illustrates points whose coordinates are the predicted and simulated BLER values; note that the points are close to the main diagonal, meaning that $BLER_{\text{pred}} \approx BLER_{\text{sim}}$.

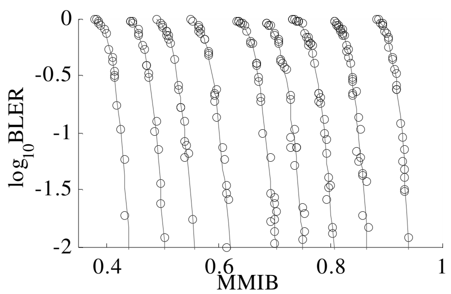

Figure 3. $BLER_{\text{pred}}$ (continuous lines) and $BLER_{\text{sim}}$ (circles); multipath fading channel, K = 1152, variable R.

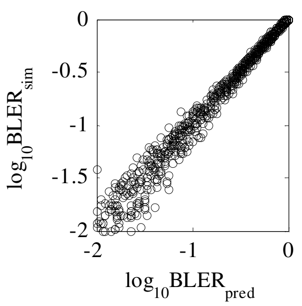

Figure 4. $BLER_{\text{sim}}$ vs. $BLER_{\text{pred}}$ on a multipath fading channel.

V. CONCLUSIONS

In this paper, we studied the prediction of the block error rate performance achieved by turbo coded OFDM transmissions in modern wireless communication systems. As the typical applications of link performance prediction are in system-level simulations and fast adaptation mechanisms, the prediction methods have to be accurate and computationally simple.

We capitalized on a link performance prediction method that uses a quality metric based on mutual information. Basically, the method operates as follows: the signal-to-noise ratio values of the employed resource elements are compressed to the mean mutual information per coded bit value, which is then mapped to the predicted BLER value by using an analytical mapping function obtained through simulations for AWGN channels. We proposed a simplification such that, for a given information block length, the proposed method requires the availability of the mapping function corresponding to the reference code rate only, regardless the code rate that is actually used. This is very convenient because the method would need the generation and storage of much less mapping functions.

We evaluated the accuracy of the simplified BLER prediction method by comparing predicted BLER values with the ones obtained through computer simulations. Results show that our method provides accurate predictions on both AWGN and multipath fading channels.

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