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A simplified channel estimation procedure for NB-IoT downlink

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Abstract. This paper presents a low-complexity channel estimation procedure which is suitable for use in energy-efficient NB-IoT user equipment devices. The procedure is based on the well-established least squares scheme, followed by linear interpolation in the time domain and averaging in the frequency domain. The quality of channel estimation vs. signal-to-noise ratio is evaluated for two channel models and compared with the performance of channel estimation function implemented in the Matlab LTE Toolbox. The computational complexities of both implementations are assessed by measuring the average processing times required to obtain channel estimates for a given number of consecutive downlink frames. The results indicate that the proposed method provides a similar quality of channel estimation with considerably shorter processing time compared to its counterpart.

1 Introduction

Narrowband Internet of Things (NB-IoT) devices require a special design to maintain low-power consumption. This refers not only to optimal hardware implementation, but also to the development of efficient and low-complexity physical layer processing algorithms. One of the fundamental procedures of downlink signal processing is channel estimation, which provides information about the distortion of the received signal, caused mainly by multipath fading, carrier frequency offset and phase noise [5]. In case of NB-IoT, a dedicated reference signal, called Narrowband Reference Signal (NRS), is introduced for the purpose of downlink channel estimation. The role of NRS is to provide reference elements (pilots) whose original values are known at the receiver side. The channel estimation starts by estimating channel coefficients for pilots. Next, the channel response is populated for the entire time-frequency resource grid within a designated time window.

The procedure of channel estimation is not standardized, thus it is up to a UE designer to implement an algorithm with an appropriate balance between SNR performance and complexity [11]. Many solutions proposed in the literature are based on Least Squares (LS) or Minimum Mean Square Error (MMSE) algorithms which were originally intended for wireless OFDM links in general [6,9]. MMSE is not preferable for NB-IoT, as it requires matrix inversion which results in higher complexity, although some modifications were proposed to reduce it [4]. LS and Linear MMSE (LMMSE) algorithms were further adapted for the LTE radio interface [7,8]. However, the power consumption requirements on wideband LTE UEs are not so stringent as for NB-IoT devices.

This document proposes a channel estimation method for NB-IoT downlink, which features a simple approach for populating channel coefficients based on pilot estimates. Sparse NRS pilots are estimated using the conventional LS algorithm. Next, the channel coefficients for all resource elements in a transmission frame are calculated through interpolation in the time (symbol) domain, followed by averaging in the frequency (subcarrier) domain. This paper evaluates the SNR performance of the proposed scheme to verify that it does not have a higher level of channel estimation error compared to the method that uses a more complex interpolation scheme. Moreover, the computational complexity was investigated by comparing the processing delays among methods. The main objective is to determine whether a simplified channel coefficient population scheme has a negative impact on the quality of channel estimation in a narrowband frequency channel designated for NB-IoT downlink.

2 NB-IoT Channel Estimation Procedure

This section presents the proposed scheme for downlink channel estimation whose objective is to compute channel coefficients. A channel coefficient, denoted by h, is a complex number whose modulus and argument correspond to the attenuation and phase shift introduced during signal transmission. Each h value refers to an OFDM resource element on a specific subcarrier k of a given symbol n

$$y_{n,k} = h_{n,k} \cdot x_{n,k} + \eta_{n,k}, \quad (1)$$

where x, y and η represent a transmitted resource element, a received resource element and additive interference, respectively.

A set of channel coefficients is calculated per frame, i.e., every 10 ms. The first step is to calculate h values for NRS resource elements only. The LS method is used, according to which the estimate of channel coefficient $\hat{h}$ is calculated as follows [9]:

$$\hat{h}^{LS}_{\bar{n},\bar{k}} = x^{-1}_{\bar{n},\bar{k}} \cdot y_{\bar{n},\bar{k}}, \quad (2)$$

where $\{\bar{n}, \bar{k}\}$ pairs address NRS resource elements. The component $x(\bar{n}, \bar{k})$ is known here as it is the element of an NRS sequence. In short, NRS channel coefficients are estimated by complex division of the received NRS resource elements by respective reference NRS resource elements. It is a simple calculation, not requiring matrix inversion, as opposed to the MMSE method.

In the next steps of the algorithm, channel coefficients are estimated for all the OFDM resource elements other than NRS ones. Firstly, time-domain interpolation is performed on NRS subcarriers. In order to keep the calculation complexity low, linear interpolation was chosen. Let $\bar{n}'$ and $\bar{n}''$ be OFDM symbol indices corresponding to subsequent NRS resource elements on subcarrier $\bar{k}$. Channel coefficients for the resources lying between these elements are calculated as follows:

$$\hat{h}_{n,\bar{k}} = \hat{h}_{\bar{n}',\bar{k}} + \frac{n - \bar{n}'}{\bar{n}'' - \bar{n}'} \cdot (\hat{h}_{\bar{n}'',\bar{k}} - \hat{h}_{\bar{n}',\bar{k}}) \qquad n = \bar{n}' + 1, \ldots, \bar{n}'' - 1. \quad (3)$$

In the third step of the procedure, channel coefficients for the remaining eight non-NRS subcarriers are determined through frequency-domain averaging. As a result, channel coefficients for all the subcarriers are equal, being the mean value of 4 coefficients estimated earlier for NRS subcarriers. Frequency averaging is suitable for channels without inter-symbol interference (ISI), i.e., when the channel magnitude response is flat. To fulfill this requirement in the case of NB-IoT, the multipath delay spread should be shorter than the reciprocal of 180 kHz frequency bandwidth, i.e., 5.6 μs. In 3GPP multipath propagation models for LTE access link, such as extended typical urban (ETU), extended vehicular A (EVA) or EPA, the delay spread does not exceed 5 μs [2]. It is therefore assumed that the averaging approach can be applied successfully.

3 Evaluation Methodology

The channel estimation quality is assessed using two indicators, which may be evaluated directly on the UE side without any prior knowledge about the transmitted downlink signal. The quality assessment is based on the analysis of restored complex symbol constellation. The error of symbol recovery is evaluated by comparing the symbols from channel equalization output with their original QPSK constellation points, which are restored by reverting the downlink signal processing chain, as shown in Figure 1.

Full downlink physical layer processing is implemented, starting from time-frequency synchronization and OFDM FFT demodulation (not included in Figure 1) to channel decoding and transport block recovery. If the transport block is received correctly, which is verified by CRC check, its bits are again channel encoded and processed further until a set of reference QPSK symbols is obtained with the values from the original QPSK constellation, i.e., $\pm 1 \pm 1i$.

Two indicators are proposed to evaluate the relation between the received symbols and the restored QPSK symbols. The first one is the root-mean-square error (RMSE) of the symbol phase. It is calculated as follows:

$$\Delta\theta_{RMS} = \sqrt{\frac{1}{N_{symb}} \sum_{i=1}^{N_{symb}} (\theta_i - \theta_{i,ref})^2} \quad [rad], \quad (4)$$

where θ represents the symbol phase and N_{symb} is the number of the analyzed complex symbols.

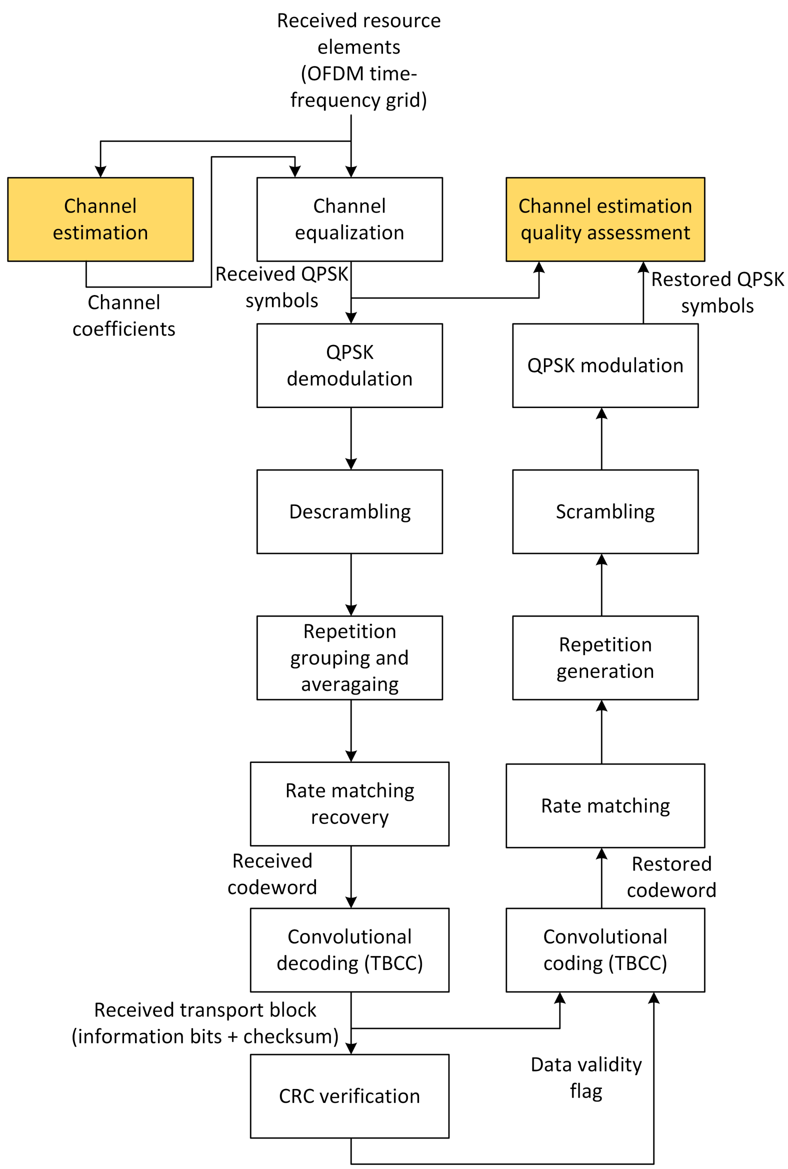

Fig. 1. Restoring original QPSK symbols for channel estimation quality assessment.

However, evaluating only the phase error may not be sufficient for implementations which make use of soft convolutional decoding, where symbol amplitudes affect path metric values in maximum likelihood sequence estimation (MLSE). Thus, a more comprehensive measure is proposed, namely the symbol correlation coefficient, which combines the impacts of phase and amplitude errors. It is calculated as follows:

$$\rho_{IQ} = \frac{1}{\alpha} \cdot \sum_{i=1}^{N_{symb}} (I_i \cdot I_{i,ref} + Q_i \cdot Q_{i,ref}), \tag{5}$$

where α is the normalization factor which limits the ρ_{IQ} values to the range between -1 and 1:

$$\alpha = \sum_{i=1}^{N_{symb}} (|I_i| + |Q_i|). \tag{6}$$

Normally the ρ_{IQ} ranges between 0 and 1. The higher value reflects more accurate symbol reception, whereas negative values would indicate the rotation between the received and reference symbol constellation.

4 Measurement Setup

To evaluate the performance of the proposed channel estimation method, a series of test waveforms were captured and processed. An R&S® CMW500 radio communication tester was used as an NB-IoT downlink signal source. Test signals were generated for 2 channel types: AWGN (without multipath fading) and EPA 5 Hz (EPA multipath profile with 5Hz maximum Doppler shift). For both channel types, 4 SNR values were considered: -5 dB, 0 dB, 5 dB and 10 dB. The radio tester was connected to the Ettus Research USRP X310 software defined radio platform, which was used to capture the waveforms of the test signals. For every [channel type, SNR] pair, a series of waveforms was recorded. They were further passed through a dedicated software-defined NB-IoT UE receive path developed in MATLAB environment.

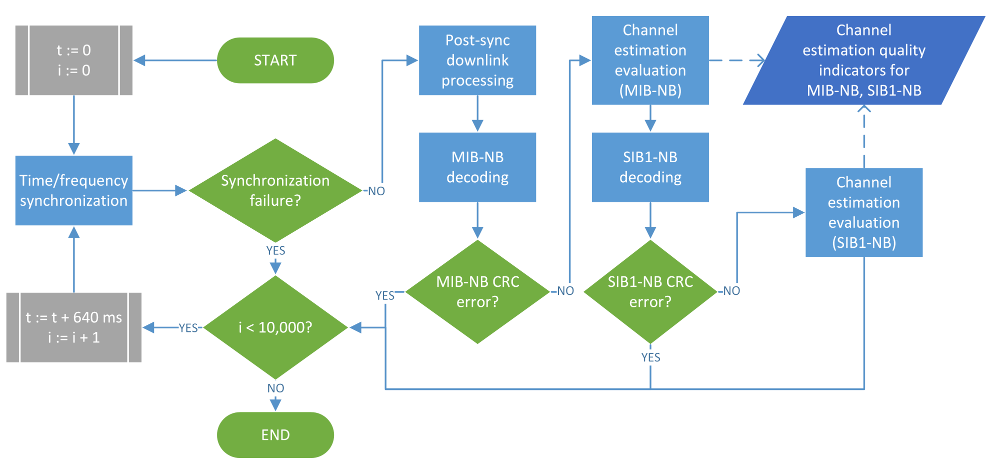

Fig. 2. Algorithm for processing a file with captured NB-IoT waveform.

The algorithm for processing waveform files is shown in Figure 2. Each iteration starts with the frequency and time synchronization step which also provides information about NB cell ID and frame number modulo 8. The synchronization is considered successful if the decoded NB cell ID matches the one set in the tester and the absolute frequency shift does not exceed 1 kHz. Once the waveform is properly aligned in time and frequency, further processing steps are conducted, with a view to decode the Master Information Block (MIB-NB) whose transmission is repeated every 64 frames. If MIB-NB reception is successful, i.e., CRC verification is passed, the block is decoded in order to extract the information necessary to retrieve the subsequent System

Information Block Type 1 (SIB1-NB). Receiving SIB1-NB requires processing 256 consecutive frames. If MIB-NB and SIB1-NB are both decoded successfully, bits of their transport blocks are used to calculate channel estimation quality indicators, according to the procedure shown in Figure 1.

The waveform processing loop proceeds to the next iteration either after successful decoding of SIB1-NB or in the case of synchronization/decoding failure. In each iteration, waveform processing starts from the sample which is offset by 640 ms in relation to the previous iteration. Such time shift corresponds to the transmission time interval (TTI) of MIB-NB (64 frames $\times$ 10 ms) [3] which ensures that a different MIB-NB is processed at every iteration. In other words, each iteration is an independent trial of synchronization followed by MIB/SIB1 decoding. The success rate of the latter may be considered an additional, higher-level measure of channel estimation quality. The better the channel estimation is, the fewer failures of MIB/SIB1 reception should occur.

5 Measurement Results

The captured waveforms were processed one after another according to the algorithm shown in Figure 2. For each waveform file, 10,000 iterations were conducted. First, the synchronization success rate was evaluated for each [channel type, SNR] pair. The results are presented in Table 1. As may be seen, the synchronization procedure performs better in the AWGN channel, while in the fading channel it is strongly related to SNR level. Nevertheless, in each case at least 9000 iterations were successful, which is sufficient for the evaluation of channel estimation.

Table 1. Percentage of successful time-frequency synchronizations.

SNR	AWGN Channel	EPA 5 Hz Channel
−5 dB	99.4%	90.1%
0 dB	100.0%	93.9%
5 dB	100.0%	98.3%
10 dB	100.0%	99.2%

5.1 Comparison of SNR Performance with the Existing Method

Once it was verified that the frequency averaging approach presents acceptable performance, proposed time interpolation with frequency averaging scheme (TIFA) was compared with the channel estimation method implemented in MATLAB LTE Toolbox$^{\mathrm{TM}}$ (MLT). To be precise, the *lteDLChannelEstimate* function is used to estimate the channel response. According to the documentation, this function implements the method described in 3GPP TS 36.104/TS 36.141 Annex E/F for the purposes of transmitter EVM testing for LTE downlink. However, the above method is intended for LTE, assuming the usage of multiple adjacent PRBs. For an NB-IoT case [1], the function provides a different processing scheme, consisting of three stages: least squares pilot estimation, pilot averaging and interpolation of channel coefficients. The first step is common for both compared methods, as mentioned in Section 2. Pilot averaging is an optional step which is intended to reduce the adverse effect of noise on pilot estimates in low SNR conditions. By default, it is enabled and configured to use a frequency-time window the size of 13 by 9 resource elements. The final step performs 2D cubic interpolation independently for each subframe, preceded by generation of virtual pilots outside the subframe boundary.

Figures 3 and 4 show the results of SNR performance comparison between MLT and TIFA. As expected, both methods perform better in the AWGN scenario than in the fading channel scenario. It may be observed that, for all the considered SNR values and channel profiles, TIFA provides lower phase RMS error than the estimation method from MATLAB LTE Toolbox$^{\mathrm{TM}}$. Error reduction is approximately 3% on average. The advantage of TIFA over MLT is especially visible for low SNR values. The same applies to symbol correlation represented by ρ_{IQ}. In the AWGN scenario, as SNR increases ρ_{IQ} approaches 1.0 value, which corresponds to a perfect match between equalized and original symbols. The average difference in ρ_{IQ} between TIFA and MLT is approximately 5–6%.

	AWGN		EPA5	
SNR	MLT	TIFA	MLT	TIFA
−5	1.43	1.38	1.47	1.44
0	1.01	0.95	1.22	1.19
5	0.56	0.54	0.87	0.83
10	0.30	0.30	0.59	0.58

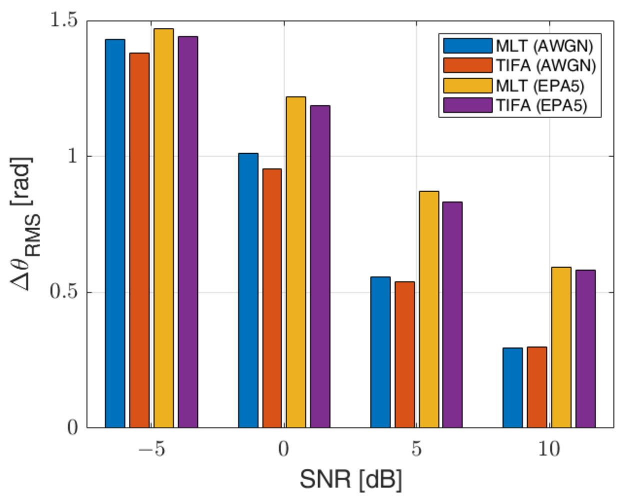

Fig. 3. Phase RMS error for MLT and TIFA channel estimation methods in AWGN channel and fading (EPA5) channel.

	AWGN		EPA5	
SNR	MLT	TIFA	MLT	TIFA
−5	0.357	0.404	0.293	0.314
0	0.699	0.779	0.476	0.504
5	0.942	0.960	0.720	0.755
10	0.998	0.998	0.879	0.895

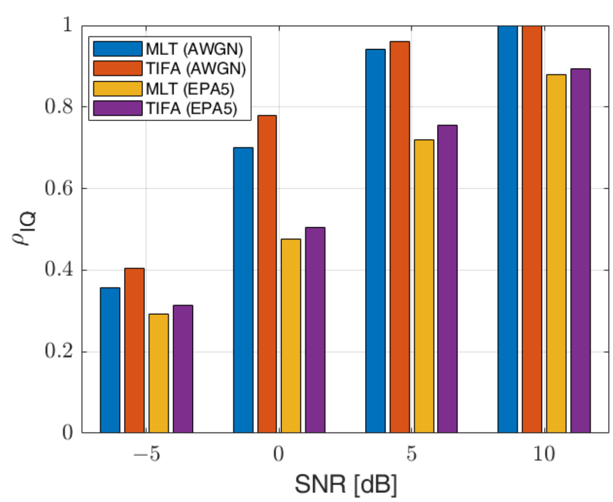

Fig. 4. Symbol correlation coefficient for MLT and TIFA channel estimation methods in AWGN channel and fading (EPA5) channel.

MIB-NB

	AWGN		EPA5	
SNR	MLT	TIFA	MLT	TIFA
–5	97.2%	97.2%	80.0%	84.1%
0	99.9%	99.9%	98.3%	98.2%
5	100.0%	100.0%	99.7%	99.6%
10	100.0%	100.0%	99.9%	99.9%

SIB1-NB

	AWGN		EPA5	
SNR	MLT	TIFA	MLT	TIFA
–5	76.1%	91.5%	26.6%	54.6%
0	98.6%	99.8%	90.2%	94.2%
5	99.8%	99.9%	97.9%	99.0%
10	100.0%	100.0%	99.5%	99.7%

Fig. 5. Percentage of decoded MIB-NB ans SIB1-NB information blocks among trials with successful synchronization.

In addition to channel estimation quality indicators, the percentage of successfully decoded information blocks, MIB-NB and SIB1-NB, was evaluated. The results are presented in Figure 5. For MIB-NB, the results for MLT and TIFA are very similar, except the case of the EPA profile with -5 dB SNR, where TIFA outperforms MLT by 4%. The difference between the two methods is more distinct in the case of SIB1-NB decoding. Especially for low SNR, a significant advantage of TIFA is observed. The number of decoded SIBs doubled when TIFA was applied to the EPA channel at -5 dB SNR. In general, the percentage of successfully decoded MIBs is higher than that of SIBs due to smaller transmission redundancy of the latter. For MIB-NB in standalone operation mode, 128 OFDM resource elements are used per one bit of transport block, while for SIB1-NB this ratio is approximately 99 resource elements per bit in the analyzed transmission scheme.

5.2 Comparison of Processing Time

To verify the low complexity of the proposed channel estimation method, the duration of MLT and TIFA processing was evaluated and compared. Since the first stage, i.e., LS pilot estimation, is the same for both methods, it was excluded from the time measurement. Moreover, the pilot averaging phase in the MLT method was excluded as well due to it being an optional step. Consequently, only the processing times required for the interpolation of channel coefficients were compared. MLT uses MATLAB's inbuilt *griddata* function to perform cubic interpolation. The source code of this function was customized so that all the unnecessary fragments, i.e., validation of input arguments and handling exceptions, could be removed to minimize the processing time.

Table 2. Duration of channel coefficient interpolation for consecutive 128 NB-IoT frames.

Method	Min	Max	Mean
MLT	547 ms	619 ms	563 ms
TIFA	69 ms	95 ms	74 ms

In order to evaluate the processing time, *tic toc* stopwatch functions were used. They counted the total time required to interpolate channel coefficients for 128 consecutive NB-IoT frames. For each channel estimation method, 80 iterations were conducted using waveforms with different SNR values and channel profiles. The platform used for the processing was equipped with an i7-10700 CPU. Table 2 presents the minimum, maximum and mean value of all the processing times. The results show that the linear interpolation and averaging procedure proposed in TIFA is about seven times faster than cubic interpolation used in the MLT method.

6 Discussion

The results presented in the previous section show that the proposed downlink channel estimation method is well suited for application in the NB-IoT UE which requires low complexity due to its limitations on cost and power consumption. When compared to the existing method, implemented in MATLAB LTE Toolbox™, the proposed solution offers several percent of improvement in terms of SNR performance. However, the major advantage of the described method is a several-fold reduction in computation time required for the interpolation of channel coefficients.

Although NB-IoT UEs have been available in the market for a few years, there is still a demand to reduce their power consumption in order to prolong their operational time. Along with power-saving features such as Discontinuous Reception (DRX), energy efficiency can be improved by developing less computationally intensive algorithms for physical layer processing, particularly in the receive chain. The method proposed in this paper provides a good balance between complexity and SNR performance. The combination of least squares estimation with linear interpolation and averaging results in a very low computational burden while still providing comparable quality compared to other LS-based methods. It should be noted that the complexity of the proposed solution is currently assessed solely by comparing processing times. The complete assessment of its advantages necessitates actual hardware implementation and a long-term analysis of power consumption.

The performance of any channel estimation method is dependent on the properties of the propagation environment, especially on the power delay profile which determines whether the channel is frequency-selective or not. 3GPP technical documents do not specify a typical profile for NB-IoT radio access channel. However, it may be assumed that for fixed UE located indoors, the channel response is generally short and changes less rapidly than in the vehicular case. Thus, assuming the propagation model for pedestrian scenario with low Doppler frequency shift is justified in the author's opinion. The same model was used to simulate the NB-IoT channel in [10]. It was proven that the proposed method is well suited for such a model. However, due to the variety of IoT applications, more challenging propagation conditions may occur, which requires further investigation.

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