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A robust ICI suppression based on an adaptive equalizer for very fast time-varying channels in LTE-R systems

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Abstract

High-speed railway communication implemented based on Long-Term Evolution-Railway (LTE-R) Platform has strict requirements for quality of services to support high data-rate transmission for numerous mobile users. In such environment, there often exists inter-carrier interference. In this paper, we exploit a robust channel estimation method in the time domain for very fast time-varying LTE-railway channels, and then, we propose an effective and adaptive frequency-domain equalizer that can offer a tradeoff between performance and computational complexity. The simulation results show the robustness of our proposed method compared with previous ones. The computational complexity of the proposed method retain at a decent number by exploiting specified properties of channel matrices.

Keywords: LTE-R, Channel equalization, OFDM, ICI cancellation

1 Introduction

Long-Term Evolution-Railway (LTE-R) is becoming a key feature supported for intelligent transportation systems (ITS) for the last two decades to replace the current Global System for Mobile Communication-Railway (GSM-R) technology. One of the most important elements of ITS is the high-speed railway (HSR), which is becoming a trending future transportation with tens of thousands kilometers length of HSR lines in Korea, Japan, and China [1]. Therefore, a number of standardizations for HSR have been set up, which are known as European Train Control System (ETCS) or International Union of Railway (UIC). The UIC is expected to complete operation and functional requirements determination by 2017. A schedule of standardization and establishment of LTE-R is given in [2, 3].

Thanks to various advantages, orthogonal frequency-division multiplexing (OFDM) has been used as a fundamental technique in physical layer of many standards. A train speed of up to 500 km/h causes a very fast time-varying channel and leads to the impairment of orthogonality among subcarriers. This is because of the Doppler shift and phase noise, which results in inter-carrier interference (ICI). The consequences of these phenomena on the performance of OFDM systems have been widely analyzed (see e.g. [4–7]). To overcome that problem, it is required that all channel state informations (CSIs) be estimated in each OFDM symbol duration. Assuming a perfect channel knowledge scenario, a channel matrix [8] specified by estimated CSIs is normally used for equalizing in the frequency domain. The only problem is that this conventional equalizer requires a huge computational complexity as a cubic function of number of subcarriers. Therefore, various researches in reducing that complexity as well as improving the performance are taken. An ICI self-cancellation scheme [9] is a technique where a number of redundant data is transmitted onto adjacent subcarriers. The main idea is that a single symbol is modulated onto a group of adjacent subcarriers with particular coefficients, so that the ICI components generated within this group can be self-cancelled. These methods, however, are compatible with a system wherein constant

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frequency offset exists. An OFDM system suffers from different Doppler frequencies that makes this method inappropriate to LTE-R network. Furthermore, the main drawback of this method is the reduction in bandwidth efficiency as a same symbol occupies several subcarriers.

Other studies have been developed using either filter in frequency domain or windowing function in the time domain [10, 11]. The main purpose of filter is to reduce the amplitude of side lobes, which leads to the significant decrease in the ICI power. This method increases the performance noticeably in comparison with ICI self-cancellation methods; however, the drawback of this method is caused by its high complexity and suitability with constant frequency shift. Authors in [12] developed a method to compensate signal dispersion caused by time-varying channels. However, this method is only applicable for media in which line-of-sight signal is extremely dominant. A partial FFT method was introduced in [13] in order to avoid the frequency-domain equalizer. Although this approach has an acceptable complexity, it only assumes that channel parameters vary slowly compared to the OFDM symbol duration. That makes this method weak against the LTE-R scenario. In [14], a low-complexity equalizer was proposed using channel matrix in the frequency domain. This method possesses a low complexity; however, the analyzed channel matrix was lacking of important corner elements. Considering a full matrix [8], such low complexity is unable to be attained. With the same channel matrix, authors in [15] proposed frequency-domain equalizer using sub-matrices. Usually, the best performance can be achieved by conventional equalizer, which finds the inverse of the entire channel matrix. However, conventional method suffers from high complexity and singular matrix problem. Proposed method in [15] solved these problems but paid the penalty of performance.

In this work, we take both issues into consideration and develop a new technique to obtain better performance without costing resource. First, we use WINNER II [16] scenario for modelling a fast time-varying channel. After that, corresponding to this channel, we utilize an optimal training sequence together with an effective estimator proposed in [17] . Intentionally, this estimation method is designed to meet requirements of the LTE-R scenario. Then, we propose an adaptive ICI canceller to bring the balance of performance and complexity. This method tends to have the performance close to conventional method, while having complexity as low as possible.

The rest of this paper is organized as follows. The mathematical description of the proposed method is presented in Section 2. Section 3 includes the simulation results as well as our discussions. We conclude this paper in Section 4.

2 Methods

The radio access technology for railway communications researched on the LTE platform is strongly expected to replace the Global System for Mobile Communications. The special attention of data transmission on railroad leads to significant problems in terms of performance simulation and measurement in particular environment. We exploited the WINNER II channel model, which was verified by the Railway Technology Research Project funded by the Ministry of Land, Infrastructure and Transport of the Korean government. All system parameters of the so-called LTE-R technology were provided by the Electronics and Telecommunications Research Institute, Korea. The very fast time-varying channel was modelled by using the Monte Carlo method. We proposed our equalization technique and evaluated by simulation using MATLAB software. In terms of assessment, we accounted the complexity and the error rate performances. The complexity was figured based on the function of basic mathematic operators, considering the worst cases. Simulation results were obtained in the same experimental conditions (i.e. using the same hardware and software version).

3 Proposal of channel equalization method

Let us assume that an OFDM system has the FFT length of N. The received signal $\vec{y}$ is expressed in vector form as follows [15]

$$\vec{y} = \mathbf{H}\vec{x} + \vec{w}, \tag{1}$$

with $\vec{y} = [y_o, ..., y_{N-1}]^T$, $\vec{x} = [x_0, ..., x_{N-1}]^T$, $\vec{w} = [w_0, ..., w_{N-1}]^T$ and

$$\mathbf{H} = \begin{bmatrix} a_{0,0} & \cdots & a_{0,k} & \cdots & a_{0,N-1} \\ \vdots & \ddots & \cdots & \cdots & \vdots \\ a_{m,0} & \vdots & a_{m,k} & \cdots & a_{m,N-1} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{N-1,0} & \cdots & a_{N-1,k} & \cdots & a_{N-1,N-1} \end{bmatrix}, \tag{2}$$

where $m, k \in \{1, ..., N\}$. The matrix component $a_{m,k} = \sum_{l=0}^{N_P-1} H_l^{(m-k)} e^{\frac{-j2\pi k(l)}{N}}$, with $H_l^{(m-k)} = \frac{1}{N} \sum_{n=0}^{N-1} h_{n,l} e^{\frac{-j\pi n(m-k)}{N}}$. The interference from mth to kth subcarrier is denoted as $a_{m,k}$. $h_{n,l}$ is the channel impulse response of paths lth in the discrete form. It is needed to find the inverse of matrix $\mathbf{H}$ since $\vec{x} = \mathbf{H}^{-1}(\vec{y} - \vec{w})$. However, one more effective way is to calculate the inverse of each sub-matrix [15], which is constructed from $\mathbf{H}$ as

$$\mathbf{M}_i = \begin{bmatrix} a_{i,i} & a_{i,i+1} & \cdots & a_{i,i+q-1} \\ a_{i+1,i} & a_{i+1,i+1} & \vdots & \vdots \\ \vdots & \cdots & \ddots & \vdots \\ a_{i+q-1,i} & \cdots & \cdots & a_{i+q-1,i+q-1} \end{bmatrix}, \tag{3}$$

where $i \in \{1, ..., N\}$. q is an odd number, which indicates the size of a sub-matrix. $\mathbf{S}_i$ defines the summation of $\mathbf{M}_i$ and the transpose matrix $\mathbf{M}_i^T$

$$\mathbf{S}_i = \mathbf{M}_i + \mathbf{M}_i^T. \tag{4}$$

We can also rewrite $\mathbf{M}_i = \mathbf{S}_i - \mathbf{M}_i^T$. Using property of matrix multiplication, sub-matrix $\mathbf{M}_i$ is expanded as

$$\mathbf{M}_i = \left(\mathbf{I} - \mathbf{M}_i^T \mathbf{S}_i^{-1}\right) \mathbf{S}_i, \tag{5}$$

with $\mathbf{I}$ as the identity matrix, which also has the size of q. Now, we calculate the inverse of sub-matrix $\mathbf{M}_i$ by

$$\mathbf{M}_i^{-1} = \left[\left(\mathbf{I} - \mathbf{M}_i^T \mathbf{S}_i^{-1}\right) \mathbf{S}_i\right]^{-1} = \mathbf{S}_i^{-1}\left(\mathbf{I} - \mathbf{M}_i^T \mathbf{S}_i^{-1}\right)^{-1}. \tag{6}$$

From (3) and (4), $\mathbf{S}_i$ will be rewritten as

$$\mathbf{S}_i = \begin{bmatrix} 2a_{i,i} & a_{i,i+1} + a_{i+1,i} & \cdots & a_{i,i+q-1} + a_{i+q-1,i} \\ a_{i+1,i} + a_{i,i+1} & 2a_{i+1,i+1} & \vdots & \vdots \\ \vdots & \cdots & \ddots & \vdots \\ a_{i+q-1,i} + a_{i,i+q-1} & \cdots & \cdots & 2a_{i+q-1,i+q-1} \end{bmatrix}. \tag{7}$$

Considering each element, it is worth noting that we can prove

$$a_{i,i+d} + a_{i+d,i} = \sum_{l=0}^{N_P-1} H_l^{(-d)} e^{\frac{-j2\pi l}{N}} + \sum_{l=0}^{N_P-1} H_l^{(d)} e^{\frac{-j2\pi l}{N}} = 0, \tag{8}$$

where d is a number varying from 1 to $q-1$. From (7) and (8), $\mathbf{S}_i$ can be clarified as a diagonal matrix as

$$\mathbf{S}_i = \begin{bmatrix} 2a_{i,i} & 0 & \cdots & 0 \\ 0 & 2a_{i+1,i+1} & \vdots & \vdots \\ \vdots & \cdots & \ddots & \vdots \\ 0 & \cdots & \cdots & 2a_{i+q-1,i+q-1} \end{bmatrix}. \tag{9}$$

Since it is a diagonal matrix, the inverse matrix $\mathbf{S}_i^{-1}$ is readily derived by taking the reciprocal of each element, which costs q divisions. On the other hand, the term $\mathbf{M}_i^T \mathbf{S}_i^{-1}$ is expressed in matrix form as

$$\mathbf{M}_i^T \mathbf{S}_i^{-1} = \begin{bmatrix} s_{1,1}^{(i)} & \cdots & s_{1,c}^{(i)} & \cdots & s_{1,q-1}^{(i)} \\ \vdots & \ddots & \cdots & \cdots & \vdots \\ s_{r,1}^{(i)} & \vdots & s_{r,c}^{(i)} & \cdots & s_{r,q-1}^{(i)} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ s_{q-1,1}^{(i)} & \cdots & s_{q-1,c}^{(i)} & \cdots & s_{q-1,q-1}^{(i)} \end{bmatrix}, \tag{10}$$

where $s_{r,c}^{(i)} = \frac{a_{i+c-1,i+r-1}}{2a_{i+c-1,i+c-1}}$. The matrix $\mathbf{M}_{i+1}^T \mathbf{S}_{i+1}^{-1}$ is given similarly as in (10). Let matrix $\boldsymbol{\Delta}_i$ define the difference of two consecutive matrices $\mathbf{M}_i^T \mathbf{S}_i^{-1}$ and $\mathbf{M}_{i+1}^T \mathbf{S}_{i+1}^{-1}$

$$\boldsymbol{\Delta}_i = \mathbf{M}_i^T \mathbf{S}_i^{-1} - \mathbf{M}_{i+1}^T \mathbf{S}_{i+1}^{-1}, \tag{11}$$

or in matrix form

$$\boldsymbol{\Delta}_i = \begin{bmatrix} s_{1,1}^{(i)} - s_{1,1}^{(i+1)} & \cdots & s_{1,c}^{(i)} - s_{1,c}^{(i+1)} & \cdots & s_{1,q-1}^{(i)} - s_{1,q-1}^{(i+1)} \\ \vdots & \ddots & \cdots & \cdots & \vdots \\ s_{r,1}^{(i)} - s_{r,1}^{(i+1)} & \vdots & s_{r,c}^{(i)} - s_{r,c}^{(i+1)} & \cdots & s_{r,q-1}^{(i)} - s_{r,q-1}^{(i+1)} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ s_{q-1,1}^{(i)} - s_{q-1,1}^{(i+1)} & \cdots & s_{q-1,c}^{(i)} - s_{q-1,c}^{(i+1)} & \cdots & s_{q-1,q-1}^{(i)} - s_{q-1,q-1}^{(i+1)} \end{bmatrix} \tag{12}$$

with

Algorithm 1 Proposed Channel Equalization

```
Require: $\mathbf{H}, \vec{y}$
Ensure: $\vec{x}=\mathbf{H}^{-1}\vec{y}$
  $i \leftarrow 1$
  $j \leftarrow k$
  for $i$:=1 to N step 1 do
    $\mathbf{S}_i^{-1} \leftarrow [\mathbf{M}_i + \mathbf{M}_i^T]^{-1}$
    if $j = k$ then
      $\mathbf{G} \leftarrow \mathbf{M}_i^T \mathbf{S}_i^{-1}$
      $j \leftarrow 0$
    end if
    $\mathbf{M}_i^{-1} \leftarrow \mathbf{S}_i^{-1}(\mathbf{I} - \mathbf{G})^{-1}$
    $\vec{x}_i \leftarrow \mathbf{M}_i^{-1}\vec{y}_i$
    if $i < N - \frac{q-1}{2}$ then
      $\vec{x}[\,i + \frac{q-1}{2}] \leftarrow \vec{x}_i[\,\frac{q+1}{2}]$
    else
      $\vec{x}[\,i + \frac{q-1}{2} - N] \leftarrow \vec{x}_i[\,\frac{q+1}{2}]$
    end if
    $j \leftarrow j + 1$
  end for
```

Table 1 Varying q with the ratio $\frac{a_{0,0}}{a_{0,1}}$

$\left\lvert\frac{a_{0,0}}{a_{0,1}}\right\rvert$	0 − 3.5	3.5 − 6	6 − 8	> 8
q	17	13	7	5

Table 3 Power delay profile of scenario D2a

Path index	Delay [ns]	Power [dB]
1	0	0
2	100	-18.1
2	200	-17.35

$$s_{r,c}^{(i)} - sr, c^{(i+1)} = \frac{a_{i+c-1,i+r-1}}{2a_{i+c-1,i+c-1}} - \frac{a_{i+c,i+r}}{2a_{i+c,i+c}} = \frac{\sum\limits_{l=0}^{N_P-1} H_l^{(c-r)} e^{\frac{-j2\pi l(i+r-1)}{N}}}{\sum\limits_{l=0}^{N_P-1} H_l^{0} e^{\frac{-j2\pi l(i+c-1)}{N}}} - \frac{\sum\limits_{l=0}^{N_P-1} H_l^{(c-r)} e^{\frac{-j2\pi l(i+r)}{N}}}{\sum\limits_{l=0}^{N_P-1} H_l^{0} e^{\frac{-j2\pi l(i+c)}{N}}}. \tag{13}$$

With a plain approximation that

$$\frac{i+r-1}{N} \approx \frac{i+r}{N} \text{ and } \frac{i+c-1}{N} \approx \frac{i+c}{N}, \tag{14}$$

(13) can be rewritten as

$$s_{r,c}^{(i)} - s_{r,c}^{(i+1)} = 0. \tag{15}$$

It means that the matrix $\mathbf{M}_i^T \mathbf{S}_i^{-1}$ is almost constant regardless of index i. Therefore, we have no significant affect to the result by assuming that $\left(\mathbf{I} - \mathbf{M}_i^T \mathbf{S}_i^{-1}\right)^{-1}$ is also constant corresponding to $i \in \{0, ..., N-1\}$. However, due to approximation errors, the assumption in (14) is valid only if

$$\left| \frac{i+r}{N} - \frac{i+r+k}{N} \right| \leq \varepsilon, \tag{16}$$

where ε is the minimum error threshold defined by engineer. k is a factor that we should consider to update the value of $\left(\mathbf{I} - \mathbf{M}_i^T \mathbf{S}_i^{-1}\right)^{-1}$. That is, after $k-1$ cycles, $\left(\mathbf{I} - \mathbf{M}_i^T \mathbf{S}_i^{-1}\right)^{-1}$ should be re-calculated. The analysis in the next section shows that the complexity order is independent of k. Therefore, the value ε and k are chosen to afford the best simulation results, as $\varepsilon = 0.01$ and $k = 10$. After figuring $\mathbf{M}_i^{-1}$, transmitted symbols x_i are recovered by

$$\vec{x}'_i = \mathbf{M}_i^{-1} \vec{y}'_i, \tag{17}$$

where $\vec{x}'_i = \left[x_i, ..., x_{i+q-1}\right]^T$ and $\vec{y}'_i = \left[y_i, ..., y_{i+q-1}\right]^T$. Here, we neglect the impact of addictive white noise. x_i is acquired by taking the middle element of $\vec{x}'_i$. By turns, $\vec{x}$ can be calculated completely. Our method can be followed by a pseudo-code below.

Table 2 System parameters

Parameter	Value
Bandwidth (MHz)	10
Number of FFT points	1024
Number of guard samples	4
Constellation	QAM 16

As mentioned earlier, the size q of a sub-matrix should be adaptive, since channel condition varies from symbol to symbol. In case the instant channel is not varying rapidly, it is not worth to use a large value of q so as to maintain the least computational complexity. To adjust this value, we consider two following conditions and give our selection by the rule of thumb in Table 1

- The computational complexity of proposed method is as low as possible.
- Symol error rate (SER) performance reaches closely to the performance of conventional equalization.

4 Simulation results and discussions

In this section, we present the Monte Carlo simulation results to compare our proposed method with the conventional one based on full-size inverse matrix and the methods in [15] (banded matrix) and [9] (AC method), since the banded matrix has the same approach which is closely related to our method, and AC method has been widely cited. System parameters are given in Table 2 and the tapped delay line channel model [18] is shown in Table 3.

In LTE-R, the train speed will be very high, up to 500 km/h. With the recommended operating frequencies which are 0.7, 1.8, and 2.6 GHz, the highest Doppler frequency is up to 1204 Hz, equivalent to a normalized Doppler of $f_{D\max}/\Delta f = 0.12$. The Doppler frequencies are summarized in the Table 4.

Figure 1 gives the power delay profile (PDP) of the multipath channel. It is derived from scenario D2a [16] which includes eight channel taps. With the system bandwidth

Table 4 Doppler frequencies

Velocity of train (km/h)	Center frequency (GHz)	Doppler frequency (Hz)
300	0.7	194
	1.8	500
	2.6	722
500	0.7	324
	1.8	833
	2.6	1204

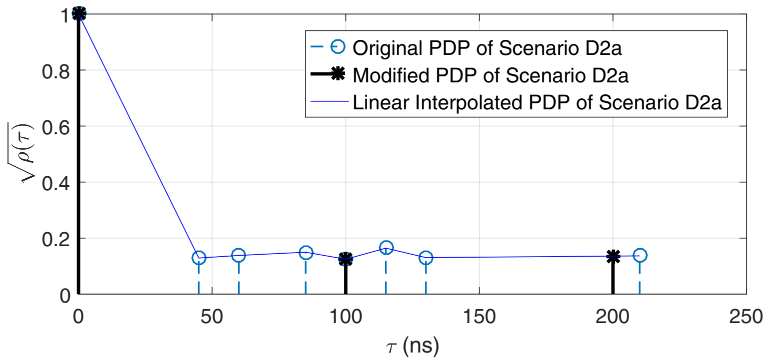

Fig. 1 Modified PDP

of 10 MHz, the interpolated PDP is obtained at the time $t = i\frac{1}{B}, i \in \{1, 2, ...\}$.

Figure 2 shows symbol error rate (SER) versus E_s/N_0 performance while taking our proposed technique and previous ones into consideration. In this scenario, we consider ICI self-cancellation (adjacent cancellation (AC)) in [9], banded matrix method in [15], MMSE-BDFE in [14], partial FFT in [13], and our proposed scheme. It can be seen that our approach gains better performance than MMSE-BDFE and partial FFT while outperforms banded matrix and AC methods. Conventional frequency domain equalizer based on channel matrix (conventional method) obtains the best performance due to considering all ICI coefficients but, however, pays the worst complexity. Its complexity varies according to a cubic function of the number of FFT points, while our proposed scheme suffers from a linear function of that. For the purpose of deploying a real-time system, our method has better resource efficiency than the conventional method.

Figure 3 gives the comparison among the techniques mentioned earlier. The maximum Doppler frequency in this case is 1204 Hz, equivalent to $f_c = 2.6$ GHz and the train speed of 500 km/h. The same result is obtained by our performance approach and by the conventional method. Partial FFT method is slightly worse than ours, but they have lower complexity (see Table 5). That can be attributed as the trade-off between performance and complexity. Similarly, MMSE-BDFE carries the lowest complexity while maintaining the medium performance. The lowest complexity can be obtained by using LDL decomposition, which is not able to be applied in our algorithm. AC method is too simple to be implemented, so no doubt it gives a very poor performance.

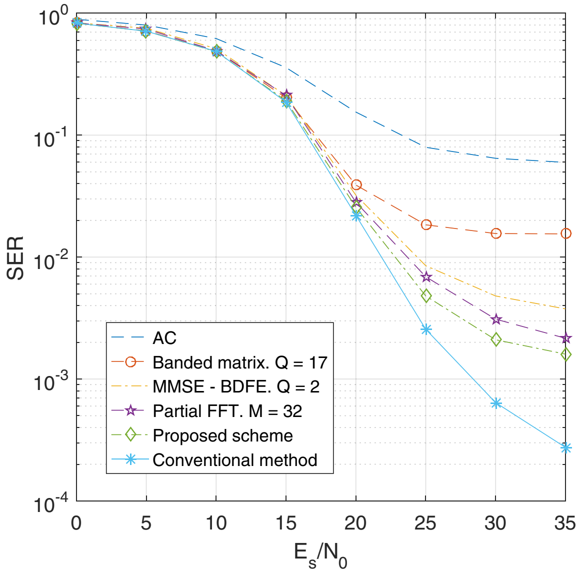

Fig. 2 SER vs. E_s/N_0 with $f_{\text{Dmax}} = 833$ Hz

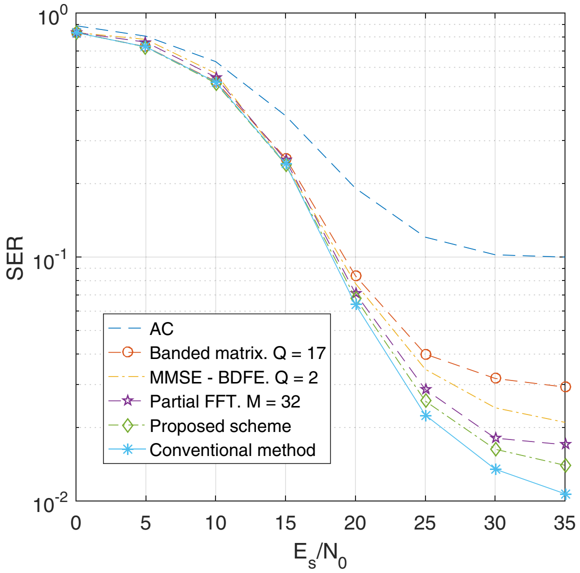

Fig. 3 SER vs. E_s/N_0 with $f_{\text{Dmax}} = 1204$ Hz

Table 5 Comparison of complexity order

Equalization algorithm	Complexity order	Number of complex operators
Conventional method	$\mathcal{O}(N^3)$	1.07×10^9
Banded matrix	$\mathcal{O}((N-q)q^3)$	4.95×10^6
MMSE-BDFE	$\mathcal{O}((8Q^2+22Q+4)N)$	8.2×10^4
Partial FFT	$\mathcal{O}(NlogK)+\mathcal{O}(NM^2)+\mathcal{O}(NMS)$	1.1×10^6
Proposed scheme	$\mathcal{O}\left(\frac{7}{3}q^3N\right)$	1.1×10^7

Figure 4 shows the SER performance for different Doppler frequencies at $E_s/N_0 = 25$ dB. Our proposed method has a tight match to the conventional equalization. While the conventional equalizer has to suffer from the complexity order of $\mathcal{O}(N^3)$, which is the highest cost compared with other techniques, our technique has the order of $\mathcal{O}(7/3q^3N)$, which is a cubic function of parameter q. It is worth noting that this parameter varies from 5 to 17 (see Table 1). In the case of successful channel estimation, q can be 5, which means that the lowest complexity is achieved. It is observed that the proposed technique gains better performance than most of others except for conventional one. Considering trading-off between performance and complexity, our technique appears to be robust against very fast time-varying channel.

5 Conclusions

In this paper, we have proposed an ICI cancellation method to combat the very fast time-varying channels in LTE-R systems. This method makes use of the relation among sub-matrices and reduces the complexity significantly compared with conventional method. However, the performance is not degraded much as one of the advantages of the proposed method. Another improvement is that it offers the engineer to configure the receiver as they can decide which is their priority between system performance and resource use. Further work is to develop this method to gain the lowest complexity bound and to combat with very ill channel conditions where channel estimation is not fully sufficient.

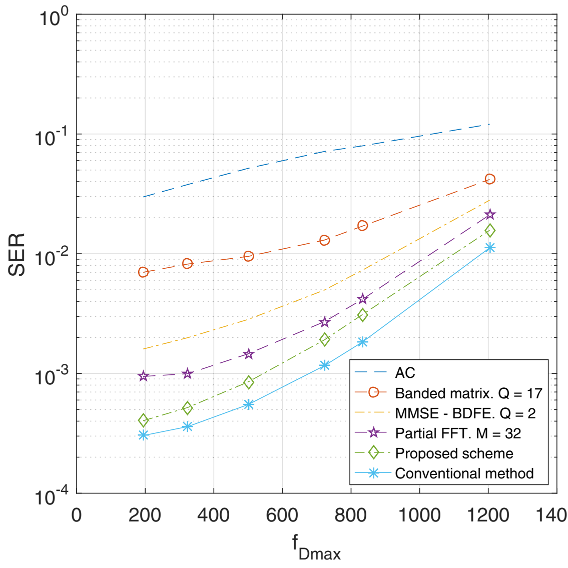

Fig. 4 SER vs. f_{Dmax}

Abbreviations

CSI: Channel state information; FFT: Fast Fourier transform; GSM-R: Global system for mobile communication-railway; HSR: High-speed railway; ICI: Inter-carrier interference; LTE-R: Long-term evolution-railway; OFDM: Orthogonal frequency-division multiplexing; PDP: Power delay profile; SER: System error rate

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Authors' contributions

HC and SR conceived the project and designed the study. HNN took charge of most analyses. H-KC and J-KC performed the simulation. VDN verified all the results. THN drafted the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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