Frame-Based Decision Directed Successive Interference Cancellation for FTN Signaling

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***Abstract*—In this paper, we propose a frame-based decision directed successive interference cancellation to improve the detection performance of Faster-than-Nyquist (FTN) signaling. The main idea of this method is to directly decide all data symbols in a complete transmission frame after minimum-mean-square-error (MMSE) equalization and regenerate the noise-free signal with the decided symbols. The difference between the equalized and regenerated signals represents the residual inter-symbol interference (ISI) which depends on the bit-error-rate of the decision. After adding the normalized residual ISI to the decided symbols, the date symbols in the transmission frame are decided recursively, leading to a decision directed successive interference cancellation (DDSIC) scheme. The simulation results in both Gaussian and multipath fading channels demonstrate that our proposed method enables lower complexity and better performance FTN systems compared with existing symbol-by-symbol interference cancellation methods.**

***Index Terms*—FTN signaling, inter-symbol interference, symbol estimation, interference cancellation.**

I. Introduction

As the telecommunication industry has entered the 5G era, the demands for higher spectral efficiency and higher data rate are increasing drastically. Among so many high-speed transmission techniques, faster-than-Nyquist (FTN) signaling proposed by Mazo [1] is emerging as a promising candidate for next generation systems with greatly improved bandwidth utilization and transmission speed.

Inter-symbol interference (ISI) cancellation is always one of the most important topics in FTN research. In terms of the interference cancellation for uncoded data sequences, Viterbi algorithm (VA) and Bahl–Cocke–Jelinek–Raviv (BCJR) algorithm are both available for mild FTN situation where the acceleration coefficient is not too small. With severe FTN, some optimized methods such as truncated VA with partial states [2], M-BCJR [3] which only searches partial trellis, as well as successive interference cancellation and equalization, can be also applied. As for coded sequences, BCJR-based turbo equalization can overcome the problem of excessive complexity in VA with convolutional coding and acceleration coefficient under Mazo limit [4].

Viterbi algorithm and BCJR algorithm have been further optimized or replaced by novel methods. M. Baek et al. proposed a novel interference cancellation scheme based on ISI QR matrix decomposition, in which they assumed that the ISI was mainly reflected on two adjacent symbols [5]. However, it was impossible to cover entire infinite ISI trellis. Instead of symbol-by-symbol detection, symbols were divided by groups and detected group-by-group. A small ISI matrix was selected every time to operate QR decomposition. Later they improved their scheme and proposed a QR decomposition-M algorithm based on BCJR. They chose the branch metrics based on minimum Euclidian distances between received signals and feedback [6]. G. Zhang et al. modified QR decomposition by decomposing ISI matrix into upper and lower triangular matrices [7]. Nevertheless, the QR decomposition still requires unacceptable computational complexity for practical implementation.

Recently, the frequency domain method is emerging as an effect means of ISI cancellation. M. McGuire and M. Sima proposed an efficient ISI cancellation method with block transmission [8]. They divided the data symbols into blocks and sent data block-by-block. The detection cost was only exponentially related to the symbol number in one block but linear in the whole system. Mingqi Li et al. proposed discrete Fourier transform (DFT) based multicarrier block transmission system by packing symbols in both time and frequency domain, leading to a 2D-FTN signaling [9].

In [10], E. Bedeer et al. established a successive symbol-by-symbol sequence estimator (SSSSE) to combat interference which iteratively removes ISI from previous symbols based on ISI matrix. However, this method was very sensitive to noise and severe ISI situation. Furthermore, they improved SSSSE and proposed a successive symbol-by-symbol with go-back K sequence estimator (SSSgbKSE). SSSgbKSE kept the same steps as SSSSE but re-estimated previous K symbols with estimated symbols. After re-estimation, a target symbol could be further estimated with these re-estimated symbols. Although these two methods showed acceptable complexity in computation, they were only suitable to low-order modulation (BPSK and QPSK) in additive white Gaussian noise (AWGN) channel. While applying higher order modulation such as 16-QAM and transmitting in multipath channel, the bit-error-rate (BER) performance will be unacceptable. Based on E. Bedeer's work, Qiang Li et al. proposed a multi-layer iterative successive interference cancellation method [11]. However, the improvement solely relied on the previously estimated symbols to estimate symbols in next layer. Consequently, the BER performance of their method did not show great advantage than that in [10].

In this paper, we propose a low-complexity frame-based decision directed successive interference cancellation (DDSIC) method. To our best knowledge, it is the first method which operates simultaneous interference cancellation for all symbols in one complete transmission frame rather than breaking the frame into small blocks. The signals after minimum-mean-square-error (MMSE) equalization and decision are regenerated and then subtracted from the original signals to estimate the residual ISI which is used for the next interference cancellation iteration. Taking the advantage of frame transmission, MMSE equalization and the proposed DDSIC can be implemented in frequency domain to greatly reduce the complexity. From simulation results, the BER performance of this scheme is better than that of the methods in [10]. Moreover, our method works well in multipath channel with high-order modulation.

The structure of this paper is as follows. In Section II, we introduce the FTN signalling model, the principle of MMSE equalizer and the implementation in frequency domain. In Section III, we present the basic idea and algorithm of the proposed DDSIC method. In Section IV, simulation results on the BER performance of SSSSE, SSSgbKSE and our proposed method are provided and compared. Finally, we draw conclusions in Section V.

II. System Model

A. Proposed FTN system with DDSIC

The diagram of the proposed FTN system is shown in Fig. 1. The data bits to be transmitted are first generated and

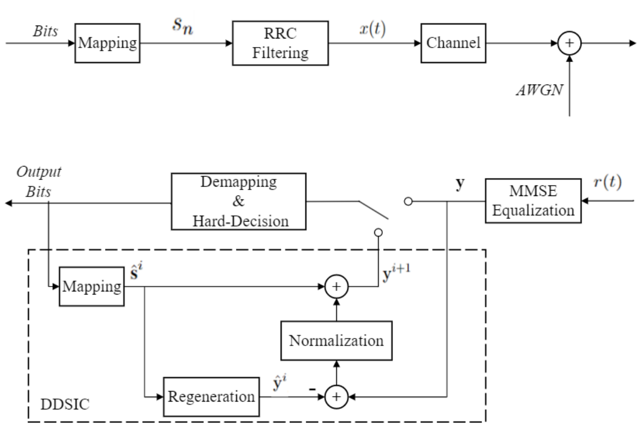

Fig. 1. Block diagram of FTN system with DDSIC.

modulated to form a frame of data symbols. After modulation, the data symbols are passed through a root-raised-cosine (RRC) filter with 3dB cut-off bandwidth $1/T$, where T is the symbol duration for Nyquist rate transmission. With FTN, the actual symbol duarion is αT, where α is a time acceleration factor, $0 < \alpha < 1$. The transmission rate now exceeds Nyquist criterion and ISI is inevitable. The FTN signal after RRC filter can be expressed as:

$$x(t) = \sqrt{E_s} \sum_{n=0}^{N-1} s_n c(t - n\alpha T) \tag{1}$$

where E_s represents the average power of the transmitted signal and s_n represents the n-th data symbol with unit average power, $n = 0, 1, 2, ..., N-1$, N is the number of symbols in one frame and $c(t)$ denotes the unit energy RRC pulse. Note that $c(t)$ should be treated as a periodic function with period $N\alpha T$ due to the frequency domain equalization to be discussed next. In practice, this can be implemented by adding a cyclic prefix (CP) before each transmission frame. The length of CP should be longer than that of the overall channel impulse response including the RRC. At the receiver end, the received signal can be expressed as

$$r(t) = \sqrt{E_s} \sum_{n=0}^{N-1} s_n g(t - n\alpha T) + w(t) \tag{2}$$

where $g(t) = \int_{-\infty}^{\infty} h(\tau)c(t-\tau)\, d\tau$, and $w(t)$ is zero mean Gaussian noise with variance σ^2. The discrete-time version of the above received signal can be expressed in matrix form as

$$\mathbf{r} = \sqrt{E_s}\mathbf{G}\mathbf{s} + \mathbf{w} \tag{3}$$

where $\mathbf{r}$ and $\mathbf{w}$ are vectors of dimension $N \times 1$ with element $r(n\alpha T)$ and $w(n\alpha T)$ respectively, $\mathbf{s}$ is a vector of dimension $N \times 1$ with element s_n, and $\mathbf{G}$ is a circular convolution matrix of dimension $N \times N$ composed of $g(n\alpha T)$ for $n = 0, 1, ..., N-1$.

B. MMSE Equalization and ISI

At the receiver, we apply MMSE equalization instead of matched filter in [10]. Usually, the matched filter output produces longer response for a data symbol and hence increases the ISI, whereas after MMSE equalizer, the ISI will be reduced. Following a well established process, the MMSE equalization matrix is given by

$$\mathbf{E} = \frac{1}{\sqrt{E_s}} \mathbf{G}^H (\mathbf{G}\mathbf{G}^H + \frac{1}{\gamma}\mathbf{I}_N)^{-1} \tag{4}$$

where $[\cdot]^H$ denotes the conjugate transpose of a matrix, $\gamma = E_s/\sigma^2$ is the signal-to-noise ratio (SNR), and $\mathbf{I}_N$ denotes the identity matrix of order N.

The MMSE equalized received signal can be expressed as

$$\begin{aligned} \mathbf{y} &= \mathbf{E}\mathbf{r} \\ &= \mathbf{P}\mathbf{s} + \mathbf{E}\mathbf{w} \\ &= p_0\mathbf{s} + (\mathbf{P} - p_0\mathbf{I}_N)\mathbf{s} + \mathbf{E}\mathbf{w} \end{aligned} \tag{5}$$

where $\mathbf{P} = \mathbf{G}^H(\mathbf{G}\mathbf{G}^H + \frac{1}{\gamma}\mathbf{I}_N)^{-1}\mathbf{G}$ is an $N \times N$ circular matrix. The first row of $\mathbf{P}$, denoted as $[p_0, p_1, ..., p_{N-1}]$, is the overall system response to a data symbol at the decision point of the receiver. The first term on the right-hand-side of (5) represents the recovered data symbols, the second represents the ISI, and the third represents the noise component.

The coefficient p_0 can be derived as

$$\begin{aligned} p_0 &= \frac{1}{N} Tr\left\{\mathbf{P}\right\} \\ &= \frac{1}{N} Tr\left\{\mathbf{G}^H(\mathbf{G}\mathbf{G}^H + \frac{1}{\gamma}\mathbf{I}_N)^{-1}\mathbf{G}\right\} \\ &= \frac{1}{N} Tr\left\{\mathbf{G}\mathbf{G}^H(\mathbf{G}\mathbf{G}^H + \frac{1}{\gamma}\mathbf{I}_N)^{-1}\right\} \\ &= 1 - \frac{1}{N} Tr\left\{\frac{1}{\gamma}(\mathbf{G}\mathbf{G}^H + \frac{1}{\gamma}\mathbf{I}_N)^{-1}\right\} \end{aligned} \tag{6}$$

which is always less than 1 and reduces the amplitude of the recovered data symbols. $Tr\{\cdot\}$ represents the trace of a matrix. According to the MMSE principle, this amplitude reduction results from the intention to minimize the ISI and noise after equalization.

C. Implementation in Frequency Domain

Due to the involvement of matrix inversion and circular convolution, direct implementation of MMSE equalization in time domain has a complexity issue. This issue can be solved by efficient frequency domain approach.

Assuming the channel state information is known and denoting it as $\sqrt{E_s}G[k]$ in discrete frequency domain, where $G[k], k = 0, 1, ..., N-1$, is the discrete Fourier transform (DFT) of $g(n\alpha T), n = 0, 1, ..., N-1$, with unit energy. The frequency response of the MMSE equalizer can be expressed as

$$E[k] = \frac{1}{\sqrt{E_s}} G[k]/(|G[k]|^2 + \frac{1}{\gamma}). \tag{7}$$

The equalization output is simply the inverse discrete Fourier transform (IDFT) of $E[k]R[k]$ where $R[k]$ is the DFT of $r(n\alpha T)$ for $n = 0, 1, ..., N-1$.

The coefficient p_0 can be also calculated as

$$p_0 = 1 - \frac{1}{N} \sum_{n=0}^{N-1} \frac{1}{\gamma|G[k]|^2 + 1}. \tag{8}$$

After MMSE equalization, an initial decision on the data symbols will be made, followed by the DDSIC to remove ISI. As the symbols are transmitted in frames, both equalization and DDSIC are performed frame-by-frame in the frequency domain which greatly reduces the complexity as compared with other symbol-by-symbol methods.

III. Proposed Decision Directed Successive Interference Cancellation

The SSSSE and SSSgbKSE in [10] are both performed symbol-by-symbol, which highly depend on the accuracy of the first received symbol. The main idea of SSSSE is to calculate the ISI matrix based on the matched filter and then remove ISI symbol-by-symbol based on each ISI component. In addition, SSSgbKSE is an improvement of SSSSE, which aims at improving the estimation accuracy by re-estimating a symbol based on the previously estimated K symbols. However, in both methods, the estimation of the first symbol is only performed by finding the nearest constellation point, which ignores the ISI influence on itself. In addition, only the interference from previous (left) symbols is considered, whereas symbols will suffer from upcoming (right) symbols in practice. Therefore, both methods suffer from severe FTN condition (i.e., with low α value). On the contrary, the proposed DDSIC algorithm estimates all symbols and removes the ISI in one transmission frame instead of depending solely on the accuracy of any individual symbol, which highly increases the estimation reliability.

We consider frame-wise transmission with frequency domain equalization because the complexity is much lower than that of time domain approach by employing the computational-efficient fast Fourier transform (FFT) rather than the linear convolution [12]. To avoid the inter-frame interference, a CP is added in front of each frame as mentioned previously.

The main idea of DDSIC algorithm is to remove the ISI from the MMSE equalized signal successively based on the decided data symbols. Denote the equalized received signal at the i-th iteration as $\mathbf{y}^i$, the decided data symbols can be expressed as

$$\hat{\mathbf{s}}^i = Dec\left\{\mathbf{y}^i\right\} \tag{9}$$

where $Dec\{\cdot\}$ denotes decision operation. Next, we need to regenerate the signal by re-passing the decided symbols $\hat{\mathbf{s}}^i$ through the RRC filter, noise-free channel and MMSE equalizer with the overall response $\mathbf{P}$ as defined in previous Section II, i.e., $\hat{\mathbf{y}}^i = \mathbf{P}\hat{\mathbf{s}}^i$. Note that the above operation is a circular convolution performed directly in time domain. It can be also performed in frequency domain through DFT/IDFT as mentioned in Section II.

Algorithm 1 Decision Directed Successive Interference Cancellation

Input:
- The symbol sequence $\mathbf{y}$ after MMSE equalizer;
- Channel parameters;
- SNR;
- Time accelerating factor α of FTN signalling;
- Roll-off factor β of RRC shaping pulse;
- Number of interference cancellation iterations $iter_{max}$;

Output:
- Symbols after the last estimation iteration;

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According to the given RRC filter and channel, calculate the response of MMSE equalizer G and p_0;
i = 1 and y^i = y;
while (i ≤ iter_max) do
    Quantize the equalized symbols into nearest constellation points;
    Regenerate signal by passing the decided symbols through RRC filter, channel (without noise) and MMSE equalizer;
    Estimate the ISI removed signal by using (10).
    i = i + 1;
end while
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Without the interference of noise, the re-generated symbol only suffers from the ISI from other symbols. Hence, the difference between the original equalized signal and re-generated signal, i.e., $\mathbf{y}-\mathbf{y}^i$, represents the residual ISI. After normalizing the residual ISI by p_0 and adding back the decided symbols, the equalized and ISI removed signal for next iteration decision is then

$$\mathbf{y}^{i+1} = \hat{\mathbf{s}}^i + (\mathbf{y} - \hat{\mathbf{y}}^i)/p_0. \tag{10}$$

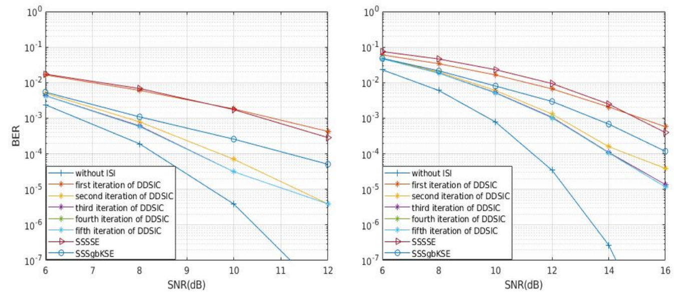
Obviously, directly decision on $\mathbf{y}$ could not accuratly recovers the data symbols due to the ISI after MMSE equalization and the noise. However, the above operation expressed in (10) has removed most ISI, i.e., we have got an 'almost correct' result. Therefore, repeating the interference cancellation process iteratively, the estimated symbol will approach the ISI-free result little by little. After several iterations, a highly accurate estimated symbol could be achieved.

The algorithm implementing the DDSIC is summarized in Algorithm 1. The computational complexity of the proposed DDSIC is also low as compared with SSSSE and SSSgbKSE as it operates frame-by-frame instead of symbol-by-symbol. The equalization and regeneration are all implemented in frequency domain with FFT/IFFT. By contrast, SSSSE and SSSgbKSE require convolution in time domain due to the symbol-by-symbol nature.

IV. Simulation Results

In this section, we evaluate the BER performance of DDSIC algorithm through simulations. For comparison among the proposed method and those in [10], we employ BPSK and QPSK modulations under AWGN channel in different ISI cases. For further practical implementation, we consider 16-QAM FTN signaling and tapped delay line (TDL) channel model with multipath time delay based on European Telecommunications Standards Institute (ETSI) recommendation [13]. Both TDL-A NLOS channel and TDL-D LOS channel are simulated. The frame length is selected as $N = 256$.

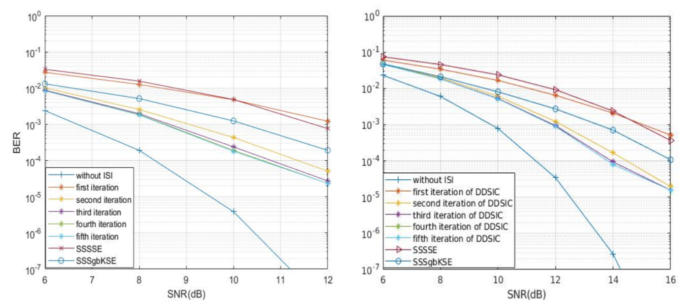
The BER performance comparison of DDSIC algorithm with $\alpha = 0.8$, $\beta = 0.25$ is shown in Fig. 2. It is shown that under both BPSK and QPSK modulations, the proposed DDSIC for the first iteration performs nearly the same as SSSSE and the performance after the second iteration is always better than that of SSSgbKSE. Under BPSK, for the target BER of 10^{-4}, there is about 2 dB SNR gain between the fifth iteration DDSIC and SSSgbKSE. For the BER of 10^{-5}, there is about 1.5 dB degradation between the fifth iteration performance and the theoretical BER curve without ISI using Nyquist rate transmission. Under QPSK, for the target BER of 10^{-4}, there is about 2 dB SNR gain between the fifth iteration performance of DDSIC and SSSgbKSE. For the BER of 10^{-5}, there is about 3.6 dB degradation between the fifth iteration performance and the theoretical BER curve without ISI using Nyquist rate transmission. It is highlighted that for the proposed DDSIC, the BER performance after the third iteration is nearly the same. In other words, most of ISI has been removed after the third iteration.



(a) BPSK (b) QPSK

Fig. 2. BER performance of DDSIC under AWGN channel with $\alpha = 0.8$, $\beta = 0.25$ adopting: (a) BPSK modulation and (b) QPSK modulation.

In a more severe ISI case, the BER performance comparison with $\alpha = 0.7$, $\beta = 0.4$ is given in Fig. 3. It is shown that the performance of DDSIC after the second iteration is still better than those of SSSSE and SSSgbKSE. Under BPSK modulation, for the BER of 10^{-4}, there is a gain of about 1.9 dB between fifth iteration DDSIC and SSSgbKSE. Under QPSK modulation, for the BER of 10^{-4}, there is a gain of about 2 dB between the fifth iteration DDSIC and SSSgbKSE.



(a) BPSK (b) QPSK

Fig. 3. BER performance of DDSIC under AWGN channel with $\alpha = 0.7$, $\beta = 0.4$ adopting: (a) BPSK modulation and (b) QPSK modulation.

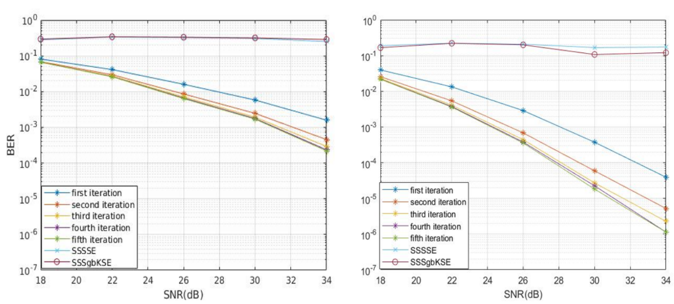
The BER performance of DDSIC algorithm with $\alpha = 0.75$, $\beta = 0.33$ in more realistic channel conditions is shown in Fig. 4. The parameters of TDL-A and TDL-D channels are presented in Table I and Tabel II respectively. It is shown that even in multipath fading channel with severe ISI, our proposed DDSIC still works well. Obviously, the improvement after each iteration is getting insignificant because the residual ISI is mostly removed by sucessive cancellation. It is highlighted that in TDL-A channel, the results after the third iteration are nearly the same. In other words, the influence of ISI is already negligible as compared with the effect of noise. For TDL-D channel, similar trends can be observed and the performance for each iteration is slightly better than that in TDL-A channel. For all the simulated cases, five iterations are enough for interference cancellation with the proposed method.

TABLE I
Parameters for TDL-A channel model

Tap#	Normalized delay	Power in dB	Fading distribution
1	0.000	-13.4	Rayleigh
2	0.3819	0	Rayleigh
3	0.4025	-2.2	Rayleigh
4	0.5868	-4	Rayleigh
5	0.4610	-6	Rayleigh
6	0.5375	-8.2	Rayleigh
7	0.6708	-9.9	Rayleigh
8	0.5750	-10.5	Rayleigh
9	0.7618	-7.5	Rayleigh
10	1.5375	-15.9	Rayleigh
11	1.8978	-6.6	Rayleigh
12	2.2242	-16.7	Rayleigh
13	2.1718	-12.4	Rayleigh
14	2.4942	-15.2	Rayleigh
15	2.5119	-10.8	Rayleigh
16	3.0582	-11.3	Rayleigh
17	4.0810	-12.7	Rayleigh
18	4.4579	-16.2	Rayleigh
19	4.5695	-18.3	Rayleigh
20	4.7966	-18.9	Rayleigh
21	5.0066	-16.6	Rayleigh
22	5.3043	-19.9	Rayleigh
23	9.6586	-29.7	Rayleigh

TABLE II
Parameters of TDL-D channel

Tap#	Normalized delay	Power in dB	Fading distribution
1	0	-0.2	LOS path
1	0	-13.5	Rayleigh
2	0.035	-18.8	Rayleigh
3	0.612	-21	Rayleigh
4	1.363	-22.8	Rayleigh
5	1.405	-17.9	Rayleigh
6	1.804	-20.1	Rayleigh
7	2.596	-21.9	Rayleigh
8	1.775	-22.9	Rayleigh
9	4.042	-27.8	Rayleigh
10	7.937	-23.6	Rayleigh
11	9.424	-24.8	Rayleigh
12	9.708	-30.0	Rayleigh
13	12.525	-27.7	Rayleigh



(a) TDL-A (b) TDL-D

Fig. 4. BER performance of DDSIC adopting 16-QAM with $\alpha = 0.75$, $\beta = 0.33$ under: (a) TDL-A channel and (b) TDL-D channel.

V. Conclusion

FTN signalling is a promising candidate to meet the demand of spectral efficiency and data rate in future generation telecommunications. One of the most appealing topics in FTN signalling is how to remove ISI. In this paper, we have proposed a novel low-complexity DDSIC scheme with MMSE equalization for FTN signaling. Because of the frequency domain implementation, the computational efficiency of DDSIC is lower than symbol-based methods which are applied in time domain directly. Compared with some existing symbol-by-symbol successive interference cancellation methods, our method shows better performance in all ISI cases with both BPSK and QPSK modulations in Gaussian channel. Furthermore, our proposed method works well in more realistic multipath fading channels with higher order modulations whereas the SSSSE and SSSgbKSE fail in these cases, which proves the feasibility of our method in practical applications. Last but not least, the results demonstrate that the BER converges very quickly after a limited number of iterations, and the performance generally improves with more increased number of iterations.

References

[1] J. E. Mazo, "Faster-than-Nyquist signaling," *Bell Syst. Tech. J.*, vol. 54, no. 8, 1975, pp. 1451-1462.

[2] A. Prlja, J. B. Anderson and F. Rusek, "Receivers for faster-than-Nyquist signaling with and without turbo equalization," *2008 IEEE International Symposium on Information Theory,* 2008, pp. 464-468, doi: 10.1109/ISIT.2008.4595029.

[3] A. Prlja and J. B. Anderson, "Reduced-complexity receivers for strongly narrowband intersymbol interference introduced by faster-than-Nyquist signaling," *IEEE Transactions on Communications*, vol. 60, no. 9, Sep. 2012, pp. 2591-2601, doi: 10.1109/TCOMM.2012.070912.110296.

[4] J. B. Anderson, F. Rusek, and V. Owall, "Faster-than-Nyquist signaling," *in Proceedings of the IEEE*, vol. 101, no. 8, Aug. 2013, pp. 1817-1830, doi: 10.1109/JPROC.2012.2233451.

[5] M. S. Baek, N. Hur, and H. Lim, "Novel interference cancellation technique based on matrix computation for FTN communication system," *2014 IEEE Military Communications Conference*, 2014, pp. 830-834, doi: 10.1109/MILCOM.2014.144.

[6] M. S. Baek, J. Yun, N. Hur and H. Lim, "Interference cancellation and signal detection technique based on QRD-M algorithm for FTN signalling," *Electronics letters*, vol. 53, no. 6, 2017, pp. 409–11.

[7] G. Zhang, Y. Wei, Y. Shen, M. Guo and S. Nie, "A reduced complexity interference cancellation technique based on matrix decomposition for FTN signaling," *2016 SAI Computing Conference*, 2016, pp. 622-625, doi: 10.1109/SAI.2016.7556046.

[8] M. McGuire and M. Sima. "Discrete time faster-than-Nyquist signalling," *2010 IEEE Global Telecommunications Conference GLOBECOM 2010*, 2010, pp. 1-5, doi: 10.1109/GLOCOM.2010.5683272.

[9] M. Li, Y. Peng, S. Lai and J. Tian, "A DFT based block transmission scheme for FTN signaling," *2017 23rd Asia-Pacific Conference on Communications (APCC)*, 2017, pp. 1-6, doi: 10.23919/APCC.2017.8303966.

[10] E. Bedeer, M. H. Ahmed and H. Yanikomeroglu, "A very low complexity successive symbol-by-symbol sequence estimator for faster-than-Nyquist signaling," in *IEEE Access*, vol. 5, 2017, pp. 7414-7422, doi: 10.1109/ACCESS.2017.2663762.

[11] Q. Li, F. Gong, P. Song and S. Zhai, "Symbol-based multi-layer iterative successive interference cancellation for faster-than-Nyquist signalling," *IET Communications*, vol. 14, no. 2, 2020, pp. 243–50,

[12] Y. Peng, X. Bian and M. Li, "Discrete Fourier transform-based block transmission for multi-carrier faster-than-Nyquist signalling," *IET Communications*, vol. 14, no. 9, 2020, pp. 1412–19.

[13] ETSI TR 138 901, "Study on channel model for frequencies from 0.5 to 100 GHz," v15.0.0, Jul. 2018.