International Journal on Advanced Science Engineering Information Technology

Vol.12 (2022) No. 1
ISSN: 2088-5334

Simple Doppler Spread Compensator for Future Railway Mobile Communication Systems (FRMCS)

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***Abstract*— The high speed railway technology is one of the important part of future railway system such as future railway mobile communication systems (FRMCS) that is based on the fifth telecommunication generation new radio (5G NR). FRMCS is suffering from the Doppler effect that causes random frequency in the received signal. Doppler effect damages the symbol orthogonality due to the change of channels within the duration of one orthogonal frequency division multiplexing (OFDM) symbol in high speed transceiver. In this paper, the Doppler Spread Compensator (DSC) technology is proposed for FRMCS, where interpolator based on Minimum Mean Square Error (MMSE) and array antenna are used to assist the DSC. This DSC technique plays an important role in the high speed railway technology to compensate the Doppler effect. We evaluate performance of the system in terms of bit-error-rate (BER) using a series of computer simulations. We also evaluate the performance of DSC assisted by array antenna elements. We confirmed from simulations that the proposed simple DSC works well even though the railway is accommodating objects with high speed of 500 km/h. The results confirmed that the array antenna helps to improve the performance of FRMCS and as a reference for the developments and implementations of antenna arrays and DSC for FRMCS.**

***Keywords*— High speed railway; Doppler spread compensator; future railway mobile communication systems.**

Manuscript received 9 Dec. 2020; revised 6 Jun. 2021; accepted 19 Dec. 2021. Date of publication 28 Feb. 2022.

I. INTRODUCTION

In the future, the railway is expected to have the ability to exchange the control and status information withthe responsible traffic management system simultaneously, where the information could be the voice, video, or data. This simultaneous data exchange ability is a key factor for the automatic railway, where this automatic railway has no driver for operate the railway. To achieve this condition, the communication systems of the future railway shouldbe developed as best as possible. The best developmentof railway communication technology not only to achievethe simultaneous data exchanged, but also to ensure thereliability of the system on every condition. Furthermore,the future railway is operated at a speed up to 500 km/h [1]. The high speed of the railway has certainly affected the performance of the communication system [2]. This high movement of the railway is causing damage to the signal due to the change of frequency which is affected by position or movement changes, which also known as the Doppler effect.

The Doppler effect is caused by Doppler shift, which is an event that the frequency of the wave from a source received by the receiver changes due to the movement of the position or movement of the receiver relative to the wave source. This phenomenon is described in 1842 by the Austrian physicist, Christian Doppler [3]. One example of the Doppler Effect event is a frequency shift of the car siren sound waves heard by the person. The sound waves from the car siren propagate in all directions, where the sound waves are centered in front of the car. When the car is going forward (to the right) with a speed of v, the sound waves is scattered behind the car. The centered sound waves have a higher frequency than the scattered sound waves, where the frequency is determining the pitch of the sound that is heard by the person. This means that person A hears the lower sound pitch than person B. The lower pitch also means that the received sound waves, which are heard by person A, is different with the transmitted sound, which is produced from the car siren.

Future railway mobile communication system (FRMCS) will replace global system for mobile communication -

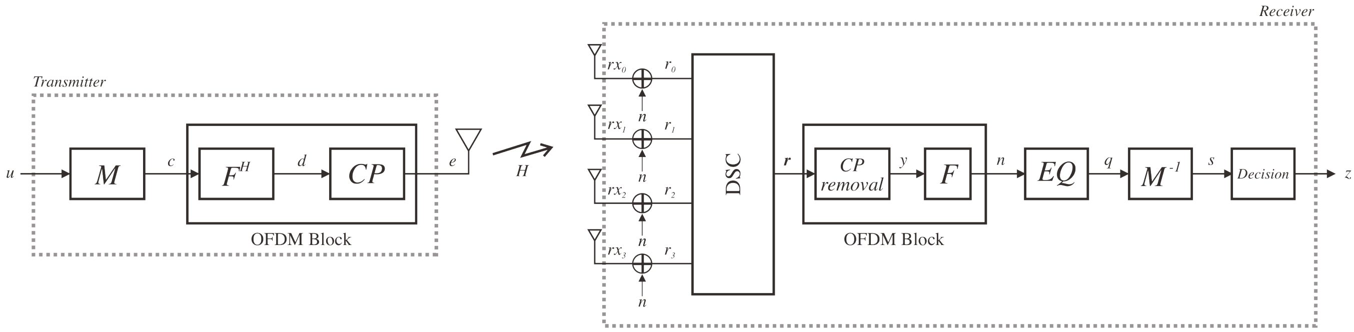

Fig. 1 Transmission structure of FRMCS using the proposed DSC.

railway (GSM-R). GSM-R is predicted to be obsolete in 2030 [4]. FRMCS has more capabilities for providing communication than GSM-R, including improved communication reliability, low data latency, high data rate, and multimedia communication [5]. The previous research of FRMCS performances based on the fifth generation new radio (5G NR) has been explained on [6], [7], where the performances evaluation of FRMCS based on 5G NR is affected by Doppler shift. 5G technology uses greater bandwidth and provides high-speed data services [8]. The high-speed railway requires railway signaling system with high data transmission for various additional applications [9]. The performances evaluation is also affected by the channel model of Indonesia, which is also proposed on [6]. The proposed Indonesia channel model is calculated using the framework on [10], [11]. Furthermore, the research assumes that the location of the base station (BS) is installed along the train-line. The research also assumes that the FRMCS frequency is used on 891-895 MHz and 936-940 MHz for uplink and downlink, respectively based on [12]. The research concluded that FRMCS promises to be the future high speed railway technology because it is able to utilize the multi path fading and diversity channels even with a simple channel coding. However, the increases of railway speed affect the FRMCS performances. This railway speed increases is causing the Doppler shift [13], which is causing the Doppler effect for the received signal on the railway. The Doppler effect is causing an error in receiving the signal on the receiver. This error is indicated from the error-floor that occurred on the bit error rate (BER) curve based on [6]. For solving this problem, the Doppler spread compensator (DSC) is needed.

The DSC has been proposed on [14]. The research proposed a novel Doppler spread compensator that is assisted by array-antenna, where the direction of array-antenna elements are parallel to the vehicle direction movement, for orthogonal frequency division multiplexing (OFDM). The DSC is needed on OFDM because OFDM is sensitive to time variation of the channel [15]. This is because the symbol interval of the OFDM signal is much longer than that of a single carrier modulated signal operating at the same bit rate [16]. For reducing the time-variation due to Doppler spread, the research design the compensator by utilizing two types of interpolator, which are the linear interpolator and Wiener interpolator. The interpolator is used for estimating the received signal at a point that is 'fixed' with respect to the ground during the observation period. Computer simulation results showed that the proposed scheme compensated for bit error degradation due to Doppler spread well. However, the research is designed for the integrated Services Digital Broadcasting for Terrestrial (ISDB-T).

We propose a simple DSC for FRMCS using a linear array antenna and utilizing a linear interpolator for estimating the received signal. We used the channel model of Indonesia on [6] for increasing the accuracy of the simulation.

Our contribution are summarized as follows:

(i) We introduce simple DSC for FRMCS by utilizing array antenna for assisting the DSC.
(ii) We provide an analysis of DSC capability in terms of BER in Indonesia channel model with various speed, where we found that the DSC assisted by array antenna are effectively for compensate the Doppler spread.

The rest of this paper is organized as follows. Section II-A explains a simple DSC system design. Section III evaluates the performances. Section IV concludes the paper.

II. Material and Method

The 5G NR-based FRMCS is considered in this paper. Fig. 1 shows the system model of 5G NR-Based FRMCS using DSC, where this system model is also used in this paper.

As shown in Fig. 1, Orthogonal Frequency Division Multiplexing (OFDM) block is used on the transmitter block. OFDM is a simple scheme for sending a lot of information through a single channel or multicarrier modulation (MCM) with a specific frequency allocation. This scheme is suitable for high-speed data transmission over multipath fading channels, where OFDM is able to change the frequency-selective fading channel to the frequency-flat fading channel in parallel transmission systems through narrow band channels [17]. OFDM is also capable of eliminating inter-symbol interference (ISI) and inter-carrier interference (ICI) through the use of cyclic prefix (CP).

Based on Fig. 1, the number of bits of information u generated at the sender side of the transmitter is random a certain number of bits with the same probability of occurrence of bits 0 and 1. The information is then mapped

TABLE I
5G-NR OFDM NUMEROLOGY CONSIDERED FOR FRMCS SIMULATION.

Parameter/ Numerology (μ)	0	1	2	3	4
Subcarrier Spacing (kHz)	15	30	60	120	240
OFDM Sym. Duration (μs)	66.6	33.3	16.67	8.33	4.17
CP Duration (μs)	4.69	2.3	1.17	0.57	0.29
OFDM Sym. incl. CP (μs)	71.3	35.6	17.8	8.92	4.46

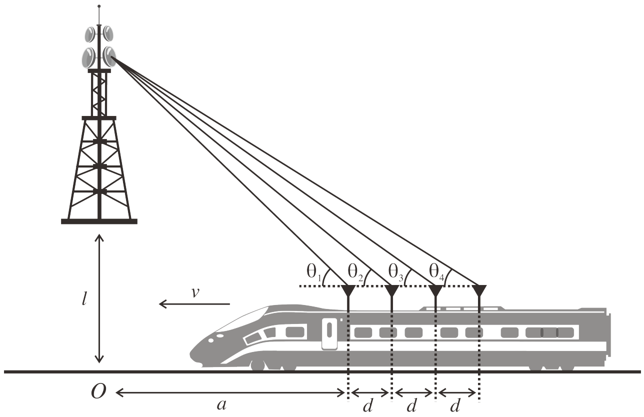

Fig. 2 The proposed array antenna-assisted DSC for FRMCS.

and modulated by modulator M to produce symbol c. The output symbol of modulator M then transformed using IFFT on OFDM block with a block length of 64. The IFFT is used for convert the symbol c in frequency domain to the symbol d in the time domain. Before transmitting the symbol, The cyclic prefix (CP) is added to the symbol d on CP block on OFDM block. The function of CP block is to add a number of the final parts of the IFFT output symbol to the front of the IFFT symbol, so that it forms a new symbol e with due regard to the provisions of CP. CP is needed for solving the problem of ISI caused by the channel dispersion on fading channel environment [18]. Based on [6], we used CP of 4.69 μs on numerology 0 since the FRMCS consider the bandwidth system of 4 MHz, where the 5G-NR OFDM numerology is showed on Table I.

The symbol e is then transmitted through the wireless channel that affected by the Doppler effect. The Doppler effect can damage the signal and cause the received signal to experience an error–floor. Error–floor is a state where the error does not decrease even though the noise is reduced.

A. The Proposed DSC

The array antenna–assisted DSC system model for FRMCS is illustrated in Fig. 2. The BS is transmitting the signal to the train, while the train moves with speed of v, which is more than 100 km/h. The signal is received by the array antenna on the train, where the gap of each array antenna element is 20 mm (d) with the distance between point O and the first of array antenna element being 100 m (a) as shown in Table II with angle of received signal of θ. Fig. 2 shows that BS and railroad have distance of 100 m (l) (from the BS to point O) as shown in Table II. The antennas are numbered from $n = 0$ to K with K being the maximum number of antenna elements.

All the received signal on each element of an array antenna-assisted DSC is also affected by the Doppler shift [19]. The Doppler shift for each antenna can be defined as

$$D(t) = \frac{f_c \cdot v}{c} \cdot cos\ \Theta_n(t), \quad (1)$$

where the $cos\ \Theta_n(t)$ can be obtained by

$$cos\ \Theta_n(t) = \frac{a + nd - vt}{\sqrt{(a + nd - vt)^2 + l^2}}, n = 0 - K, \quad (2)$$

with K is the maximum number of array antenna element.

B. Transmitter

We consider 5G NR-based FRMCS in this paper, where the system model is illustrated in Fig. 1. We also consider *u* as the information bits sent in the block length of $N = 64$. Block *M* is modulated by *M* using complex binary phase shift keying (C-BPSK) modulation as shown on Table II. The C-BPSK is used in 5G NR based on [20]. Binary phase shift keying (BPSK) modulation in 5G NR is different from conventional BPSK which only produces symbols of real value. The BPSK modulation in 5G NR produces complex symbols, which are consists of real value and imaginary value, so that the 5G NR BPSK called by complex-binary phase shift keying (C-BPSK). Based on [20], C-BPSK modulation can be produced by

$$x = \frac{1}{\sqrt{2}}[(1 - 2b(i)) + j(1 - 2b(i))], \quad (3)$$

where the information bit $b(i)$ is mapped to the modulation symbol x.

Before the signal is transmitted through the channels, modulated signal (*c*) is transformed from the signal on frequency domain into the signal on time domain (*d*), and added cyclic prefix (*CP*) on the signal. Transmitted signal (*e*) is transmitted through the channels H to the receiver. We consider r_k is the received signal on the *k*–th antenna element, which can be described as

$$r_k = H \cdot x + n, \quad (4)$$

where H is the channels affected by Doppler shift with path value of h = [1 0.011686918 0.077624712 0.000246207 4.93515E-6] based on [6].

C. Receiver

On Fig. 1, r_k is the input of DSC on the receiver block. We assumed that the number of maximum antenna $K = 4$ with the index of $k = [0, 1, \cdots, K - 1]$, where k is the antenna element index with the maximum number of antenna element is K. We used 4 elements of the antenna for assisting the DSC. The antenna receives the signal r_k and

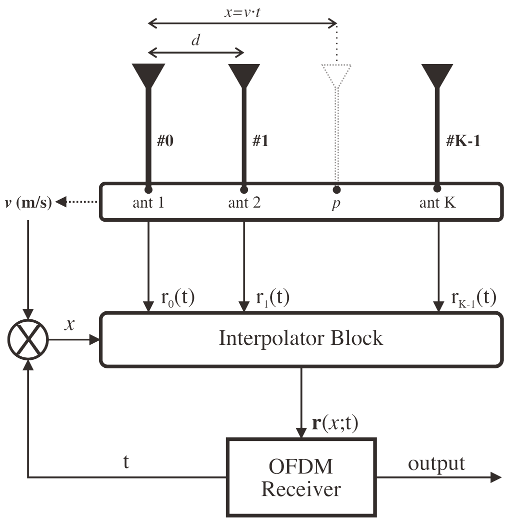

Fig. 3 The detailed struture of the proposed array antenna-assisted DSC.

then forwarded it to the DSC. Fig. 3 shows the DSC structure which is assisted by an array antenna.

The received signal on DSC which was forwarded from the antenna is processed on Interpolator block. On the interpolator, the received signal is defined as a vector and can be described as

$$\mathbf{r}(t) = [r_0(t), r_1(t), ..., r_{K-1}(t)]^T. \quad (5)$$

The MMSE is used in the interpolator to estimate the received signal on position x. However, weighting factor of MMSE needs to be found so that the output of MMSE interpolator can be estimated. The MMSE can be defined as

$$r(x,t) = \mathbf{w}^T(x)\mathbf{r}(t), \quad (6)$$

with $w(x)$ is *weight vector* that used for estimating the received signal on position x. Based on [14], the weight vector can be calculated by

$$\mathbf{w}(x) = \mathbf{R}^{-1}\mathbf{b}(x), \quad (7)$$

with $\mathbf{b}(x)$ is cross–correlation vector between the vector of received signal and output MMSE $r(x,t)$ and $\mathbf{R}$ is the correlation matrix between each antenna element. The cross–correlation vector $\mathbf{b}(x)$ can be calculated by

$$\mathbf{b}(x) = J_0(2\pi(kd - x)/\lambda), \quad (8)$$

where $J_0(x)$ is first type of zero–th order Bessel function, and correlation matrix $\mathbf{R}$ can be calculated by

$$\mathbf{R}_{kn} = J_0(2\pi d(n-k)/\lambda). \quad (9)$$

The output of the interpolator is the output of DSC and processed on the OFDM block on the receiver. On the receiver OFDM block, the CP of received signal $\mathbf{r}$ is removed and signal y, which is the output signal of CP removal block, is transformed into the signal on frequency domain on FFT block (F), where the output from this block is signal n. The signal n is equalized on an equalizer block (EQ) for restoring the damaged signal due to the distortion incurred by a signal transmitted through a channel. On the block M^{-1}, the signal is demodulated with a simple decision and produced the output signal z.

TABLE II
PARAMETERS USED IN SIMULATION OF DSC-BASED FRMCS.

Parameter	Value
Frequency	938 MHz
Bandwidth	4 MHz
Subcarrier Spacing	15 kHz
FFT Size	256
OFDM Symbol Duration	66.67 μS
Modulation	C-BPSK
Antenna Element Spacing (d)	0.2λ
Distance between BS and Railroad (l)	100 m
Distance between O point and First Element of Array-Antenna (a)	100 m

III. Result and Discussion

The Fig. 4 shows systematic of received signal on two array antenna elements, which is containing the transmitted bits of (*a, b, c, d* and *e*), on each array antenna element which is assist the DSC for compensate the Doppler spread. Fig. 4 shows two condition of received signal, i. e., nearly idle and high speed railway. On nearly idle condition, the first antenna element (left side) received the signal is close to the transmitted signal. However, the transmitted bits *e* is not received on the first antenna. To recover the bits of *e* which is not received, we use the second antenna to received the bit. On high speed condition, the received bits are scattered. The first antenna element (left side) only received the signal containing bits *a, c,* and *e*, and the second antenna is received the signal containing bits *b* and *d* bits from the transmitted bits. These received bits are re-calculated to obtain the new pattern of bits, which is close to the transmitted bits by using Array antenna-assisted DSC.

The results of this paper are divided into five parts. First, we presented the BER performances of FRMCS with and without DSC on railway speed of 350 km/h, and 500 km/h. Second, we presented BER performances of FRMCS with DSC on some number of array-antenna, which is assisted the DSC for compensate Doppler spread. Third, we presented the effectiveness of proposed DSC on FRMCS and presented the BER performances according to normalized Doppler spread ($f_d T_s$). Forth, we presented the BER performances of FRMCS interfered by mobile phone BS signal on railway speed of 100 km/h, 300 km/h, and 500 km/h. The last result, we presented the BER performance of FRMCS with and without DSC affected by the transmitted signal blocklength.

A. Performance of DSC on FRMCS

The performances of BER FRMCS without DSC compared to BER FRMCS with DSC is aimed to confirm that the compensator on the proposed system increases the performances of FRMCS system for future railway. The

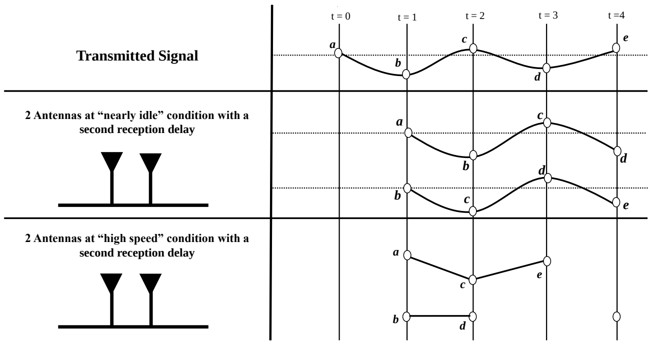

Fig. 4 Effect of Doppler spread experienced by each antenna element.

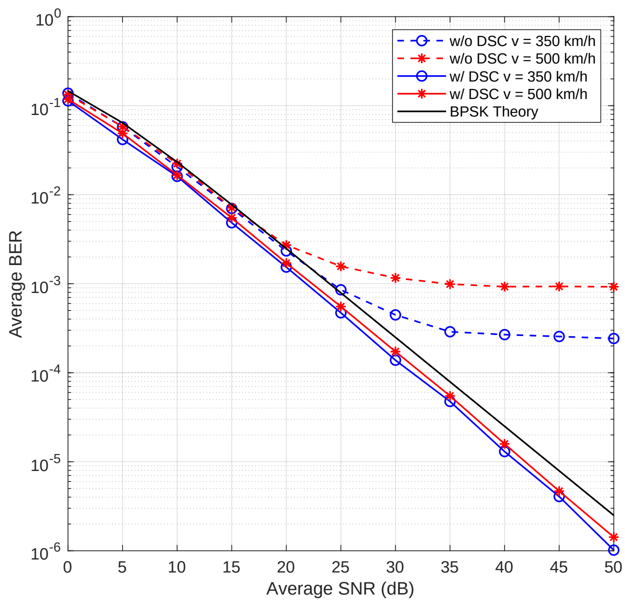

Fig. 5 The BER performances of FRMCS with and without DSC.

BER performances, which is presented in this part, are used the system configuration according to Table II and evaluated under the Bandung channel model based on [6] affected by Doppler shift.

Fig. 5 shows the performance of BER FRMCS under Bandung channel model, where theoretical BER of uncoded BPSK is shown as a reference. BER performance of FRMCS without DSC when the railway at speed of 350 km/h reach 1×10^{-3} at the SNR of 30 dB, which is indicated from the circle blue dashed line. However, the error-floor is occurred at SNR of 35 dB. BER performance of FRMCS without DSC when the railway at speed of 500 km/h reach 7×10^{-3} at the SNR of 15 dB, which is indicated from star red dashed line. However, the error-floor is occurred at SNR of 30 dB.

The BER performances of FRMCS with DSC is also showed in Fig. 5. BER performance of FRMCS with DSC when the railway at speed of 350 km/h, which is indicated from circle blue line, reach 5×10^{-5} at the SNR of 35 dB.

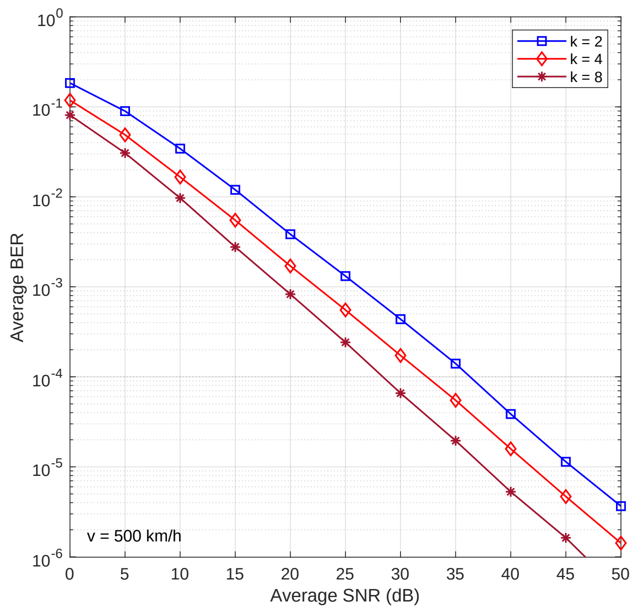

Fig. 6 The BER performances of FRMCS with K array-antenna element.

When the railway at speed of 500 km/h, BER performance of FRMCS with DSC reach 1×10^{-5} at the SNR of 40 dB, which is indicated from star red line.

These results confirmed that the increases speed of railway is decreased the FRMCS BER performances. These results also confirmed that the DSC on FRMCS is work-well to compensate the Doppler spread. This is indicated from the increases of BER performances of FRMCS. The DSC also work well at high speed railway indicated by the decreases BER of 1×10^{-3} into 1×10^{-5} when the railway speed of 500 km/h.

B. Comparison of BER Performances of Some Number of Maximum Array-antenna Elements on FRMCS with DSC

We also simulated the BER performances of FRMCS with DSC, where the DSC is assisted by array antenna, considering the number of array-antenna elements. We assumed some maximum number of array antenna elements K of 2 elements, 4 elements, and 8 elements with the speed of railway of 500 km/h.

Fig. 6 shows the BER performances of FRMCS with DSC on some maximum number of array-antenna elements. The BER performance of FRMCS with DSC when the number of antenna element $K = 2$, which is indicated from square blue line, reach 1×10^{-4} at SNR of 35 dB. When the number of antenna element $K = 4$, the BER performance of FRMCS with DSC reach 5×10^{-5} at SNR of 35 dB, which is indicated from diamond red line. The BER performance of FRMCS with DSC when the number of antenna element $K = 8$, which is indicated from star brown line, reach 1×10^{-5} at SNR of 35 dB.

These result show that the increases number of array antenna elements is increasing the BER performances of

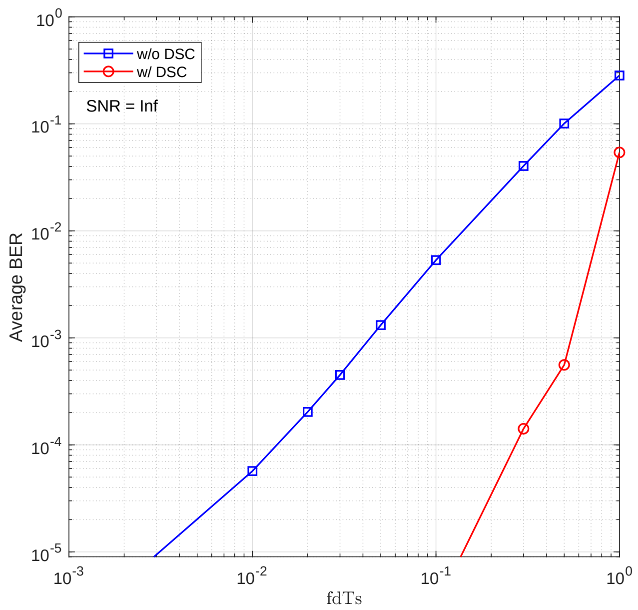

Fig. 7 The BER performances of FRMCS with and without DSC at different $f_d T_s$.

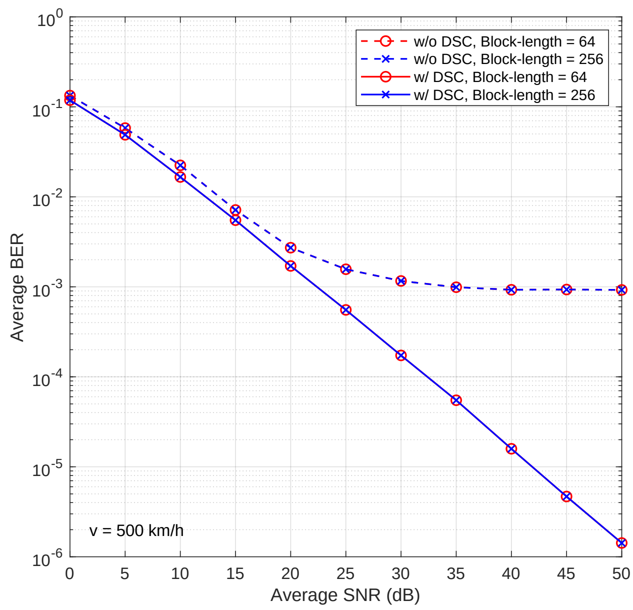

Fig. 8 Performances of FRMCS with and without DSC showing that the performance is not affected by the blocklength due to the normalized Doppler.

FRMCS with DSC, where the DSC is assisted by array antenna. This is indicated from BER performance reach 1×10^{-4} ,for maximum array antenna-assisted DSC elements $K = 2$, into BER performance reach 5×10^{-5}, for maximum array antenna-assisted DSC elements $K = 4$ at SNR of 35 dB. However, the number of array antenna elements should be determined by considering the mutual coupling between each element antenna for maximize the DSC performances on FRMCS on real condition.

C. Comparison of FRMCS Performances without DSC and with DSC Based on Normalized Doppler Spread ($f_d T_s$)

The Fig. 7 shows the BER performances againts Normalized Dopper Spread ($f_d T_s$). We consider using average SNR of ∞. We confirm that the used of DSC can help the system achieved better performance. The BER performances of $f_d T_s$ when the block length of N = 256 and the theoretical uncoded BPSK is used as a reference. The BER performances of $f_d T_s$ of 10^{-1} without DSC, which is indicated from square blue line, reach 5×10^{-3}. The BER performances of $f_d T_s$ of 10^{-1} with DSC reach at lower than 1×10^{-5}, which is indicated from circle red line. The DSC can increase the BER performances. However, the DSC ineffective when the $f_d T_s$ get higher.

D. Blocklength of transmitted signal Effect on FRMCS

The effect of blocklength of transmitted signal on FRMCS is shown on Fig. 8. We found that the blocklength of the transmitted signal doesn't affect the BER performances of FRMCS for both with DSC and without DSC. We use normalization of Doppler spread $f_d T_s$ against symbol duration, and normalization useful $f_d \bar{T}_s$ symbol duration to facilitate $f_d T_s$ simulation on various number of samples. In this case, the Doppler effect with any $f_d T_s$ can be simulated with a number of any sample, so it's not a big problem if it's simulated with a small blocklength. Fig. 9 shows the channel change in $f_d T_s = 0.5$ with blocklength 64, while Fig. 10 shows the channel change at $f_d T_s = 0.5$ with blocklength 256, which indicates that the effects of both are the same

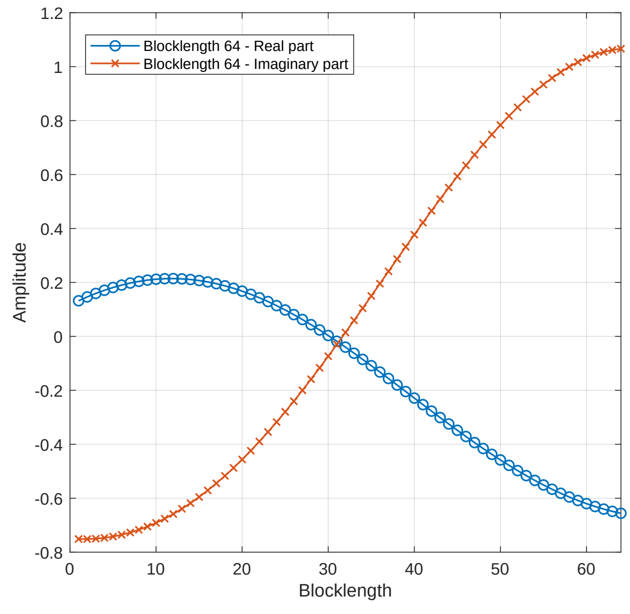

Fig. 9 The change of channels at $f_d T_s = 0.5$ with blocklength 64.

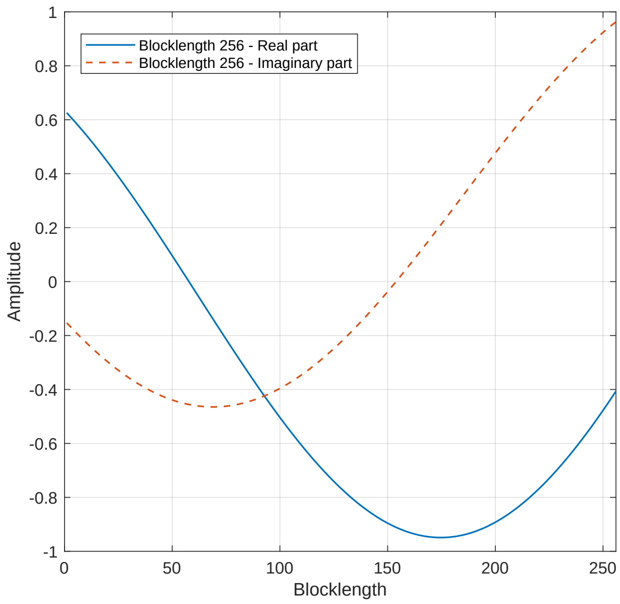

Fig. 10 The change of the channels at $f_d T_s = 0.5$ with blocklength 256.

although with different sample sizes.

IV. Conclusion

We have proposed a simple DSC for FRMCS, where array antenna is used to assist the DSC. We performed a series of computer simulations to evaluate the performance of the proposed DSC in terms of BER performances. We considered speeds of 350 km/h and 500 km/h. We found that the DSC assisted by array antenna on FRMCS works well to compensate the Doppler spread on the received signals, indicated by the decreases of BER from 1×10^{-3} to 1×10^{-5}, when the railway is with a speed of 500 km/h. We also foud that the increased number of array antenna elements improve the BER performances. We also found that the blocklength of transmitted signal does not affect to the BER performances of FRMCS due to the normalized Doppler effect to indicate that the simulation is correct. The results of this paper are expected to become references for the developments and implementations of antenna arrays and DSC for FRMCS.

Acknowledgment

This research is supported in part by the BRIN Research Grant on Indonesia High Speed Train, 2021–2022.

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