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PILOT SYMBOL ERROR RE-ORTHOGONALIZATION IN 2×2 MIMO SYSTEMS OF WIRELESS COMMUNICATION

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ABSTRACT

A 2×2 MIMO wireless communication system with channel estimation is simulated, in which two transmit, and two receive antennas are employed. The orthogonal pilot signal approach is used for the channel estimation, where the Hadamard sequences are used for piloting. Data are modulated by coherent binary phase-shift keying, whereupon an orthogonal space-time block coding subsystem encodes information symbols by using the Alamouti code. Based on the simulation, it is ascertained a possibility to decrease the bit-error rate by substituting the Hadamard sequences for the sequences having irregular structures, and constituting the eight known orthogonal bases. Considering a de-orthogonalization caused by two any pilot sequence symbol errors, the bit-error rate is decreased by almost 2.9 %. If de-orthogonalizations are caused by two repeated indefinite, and definite pilot sequence symbol errors, the decrements are almost 16 % and 10 %, respectively. Whichever sequences are used for piloting, the 2×2 MIMO system is ascertained to be resistant to the de-orthogonalization if the frame is of 128 to 256 symbols piloted with 32 to 64 symbols, respectively.

Key words:

wireless communication, channel estimation, MIMO, orthogonal pilot sequences, bit-error rate.

Research article

INTRODUCTION

In radio, multiple-input and multiple-output (MIMO) specifically refers to a practical technique for sending and receiving more than one data signal simultaneously, over the same radio channel by exploiting multipath propagation. More generally, MIMO is a method for multiplying the capacity of a radio link by using multiple antennas at the transmitter and receiver ends of a wireless communication system [2]. MIMO systems are increasingly being adopted in wireless communication standards, including IEEE 802.11n (Wi-Fi), IEEE 802.11ac (Wi-Fi), HSPA+ (3G), WiMAX, and Long Term Evolution (4G LTE), for the potential gains in capacity they realize when using multiple antennas. Multiple antennas use the spatial dimension in addition to the time and frequency ones, without changing the bandwidth requirements of the system [14].

When multiple transmitter antennas are used, the concept of orthogonal space-time block coding (OSTBC) is employable [4]. An OSTBC subsystem encodes information symbols from a modulator by using, either the Alamouti code [1] for two transmit antennas, or other generalized complex orthogonal codes [11] for three, or four transmit antennas. To know how a signal propagates from the transmitter to the receiver, and represents the combined effect of scattering, fading, and power decay with distance, the channel state information is required. The channel state information makes it possible to adapt transmissions to current channel conditions, which is crucial for achieving reliable communication with high data rates in multi-antenna systems. In the realistic scenario, where the channel state information is not known at the receiver, this has to be extracted from the received signal. The channel estimator can perform this by using orthogonal pilot signals that are prepended to every packet [5]. Compared to a blind approach, where the estimation is based only on the received data, without any known transmitted sequence, the tradeoff is the accuracy versus the overhead. The orthogonal pilot signal approach has a higher overhead than the blind approach, but it achieves a better channel estimation accuracy than the blind approach [16].

However, in practice, orthogonal pilot sequences, from which the channel between the transmitter and receiver is estimated, are limited by the coherence time of the channel. Most importantly, the reuse of pilot sequences of several co-channel cells may create pilot contamination that worsens the MIMO performance [9]. Another problem is that a loss of a symbol in a pilot sequence (due to channel noise and interference) leads to de-orthogonalization. Obviously, the pilot signal de-orthogonalization may also worsen the MIMO performance [3].

MOTIVATION

Orthogonalization is a crucially important property used in wireless communication systems to increase capacity of a radio channel without badly affecting its reliability. In MIMO, orthogonal codes are usually taken from the Hadamard matrix [12], where the first orthogonal sequence of pilot symbols is the sequence of ones. In fact, it is the Walsh function of the zeroth order, which is a function-constant [13]. In particular, Walsh functions are generated from the Hadamard matrix [15], and can be used as well for other transmit antennas.

Walsh functions have a regular structure as they are mirror-symmetrical (considering from the middle of the unit interval on which the functions are defined). Similar binary functions having irregular structures (IS), and constituting orthogonal sets are known also (e. g., see [6]). The eight orthogonal bases of such irregular-structure binary functions (considering the seven non-zeroth-order functions in every basis; the function-constant, which is the zeroth-order function in every basis, is not considered) found by Romanuke [7] were simulated to substitute the respective Walsh functions in wireless communication systems with the code division multiple access (CDMA). It was shown in [8] that these orthogonal sets of binary functions outperform Walsh set, where the bit-error rate (BER) is decreased by 3 % to 5 %. It is naturally assumed that BER in MIMO systems with the orthogonal pilot signal approach might be decreased by using the similar substitution.

The assumption is to be verified on a 2×2 MIMO system with channel estimation, in which two transmit, and two receive antennas, are employed. It is assumed that the channel remains unchanged for the length of the packet (i. e., it undergoes slow fading), and the channel undergoes independent fading between the multiple transmit-receive antenna pairs. Data are modulated by coherent binary phase-shift keying (BPSK) [10]. Then OSTBC by Alamouti is applied to the modulated data and the signal is passed over flat-fading Rayleigh channels [12].

The goal is to estimate the BER performance of a 2×2 MIMO system with channel estimation by the orthogonal pilot signal approach for both the Hadamard and Romanuke orthogonal codes. The case of a symbol loss (or, in other words, a symbol error) in a pilot sequence (that implies a de-orthogonalization) is to be studied as well. For this, various situations are to be considered: de-orthogonalization caused by one and two pilot sequence symbol errors, where subcases of symbol definiteness and repeatability should be simulated.

BPSK-OSTBC SIMULATION PARAMETERS

The simulation is based on MATLAB® R2019a Communications System Toolbox™ functions covering an end-to-end 2×2 MIMO system. The fundamental parameters for simulating BPSK and OSTBC are as follows: frame length F, number of pilot symbols per frame P, bit-energy-to-noise-density ratio (BENDR) $r_{\mathrm{Eb/No}}$ in dB, maximum number of errors m_{err}, maximum number of packets N_{pack}. The simulation is run over a range of BENDR points to generate BER results that allow comparing different cases.

It is reasonable to vary BENDR from 0 dB to 6 dB with a step of 1 dB. The frame length is equal to 32, 64, 128, 256 symbols. The number of pilot symbols per frame cannot exceed 25 % of the frame length, so it is set according to tab. 1.

Tab. 1. The 10 cases of the parameter pair of the frame length and pilot symbols per frame

F	**32**	**64**	**128**	**256**	**frame length**
P	8	8	8	8	number of pilot symbols per frame
	P	16	16	16	
		P	32	32	
			P	64	

For the 2×2 MIMO system, the two Hadamard orthogonal sequences, regardless of the number of pilot symbols per frame, have the view presented in fig. 1. In fact, these are the Walsh functions of the zeroth order and ($P-1$)-th order (i. e., the last function in the Walsh basis of functions corresponding to P –positioned orthogonal codes). The IS binary functions (ISBFs) by Romanuke shown in fig. 2 have the same function-constant, so it is better to use the last two functions from each basis of P functions (fig. 3).

The above-mentioned de-orthogonalization occurs when the negative value of a binary function is dropped into the positive value, and vice versa. These pilot sequence symbol errors are notationally referred to as “0→1” and “1→0”, respectively. To estimate the BER performance under circumstances of imperfect orthogonality, the six cases (tab. 2) are to be simulated for both the Hadamard and Romanuke orthogonal codes. The number of BPSK-OSTBC simulations should be sufficiently great for obtaining stable results. The stability of these results is expected to be confirmed by carrying out another series of simulations.

Fig. 1. The two Hadamard orthogonal sequences for different cases of pilot symbols per frame

Tab. 2. The six cases to be simulated

case #	Description	Notation of pilot sequence symbol errors
1	Without de-orthogonalization	there are no pilot sequence symbol errors
2	De-orthogonalization caused by one indefinite pilot sequence symbol error	"0→1" or "1→0"
3	De-orthogonalization caused by one definite pilot sequence symbol error	"0→1"
4	De-orthogonalization caused by two repeated indefinite pilot sequence symbol errors	"0→1" and "0→1" or "1→0" and "1→0"
5	De-orthogonalization caused by two repeated definite pilot sequence symbol errors	"0→1" and "0→1"
6	De-orthogonalization caused by two indefinite pilot sequence symbol errors	"0→1" and "0→1", or "1→0" and "1→0", or "1→0" and "0→1", or "0→1" and "1→0"

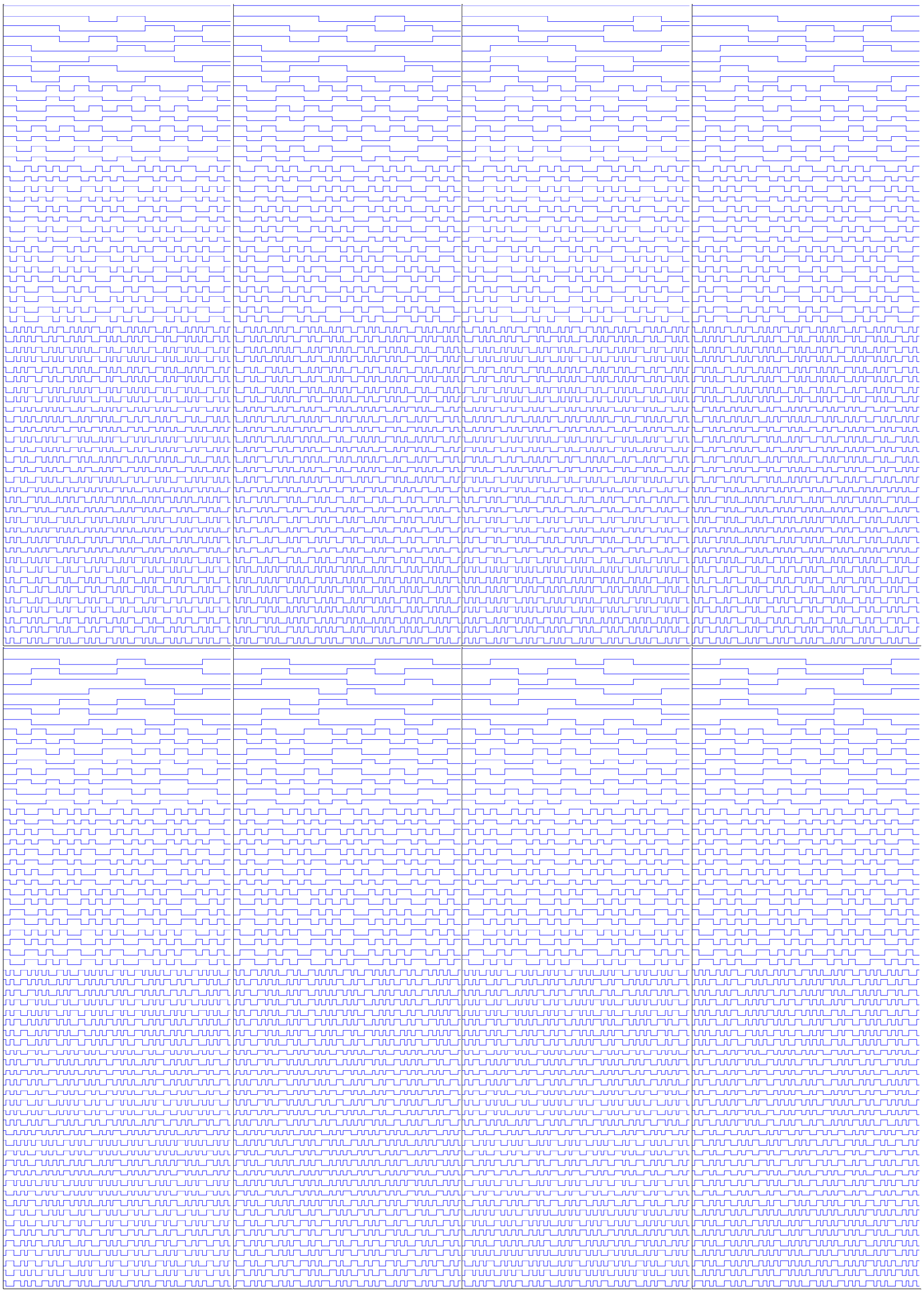

Fig. 2. The eight orthogonal bases presented for the case of 64-positioned orthogonal codes [13]

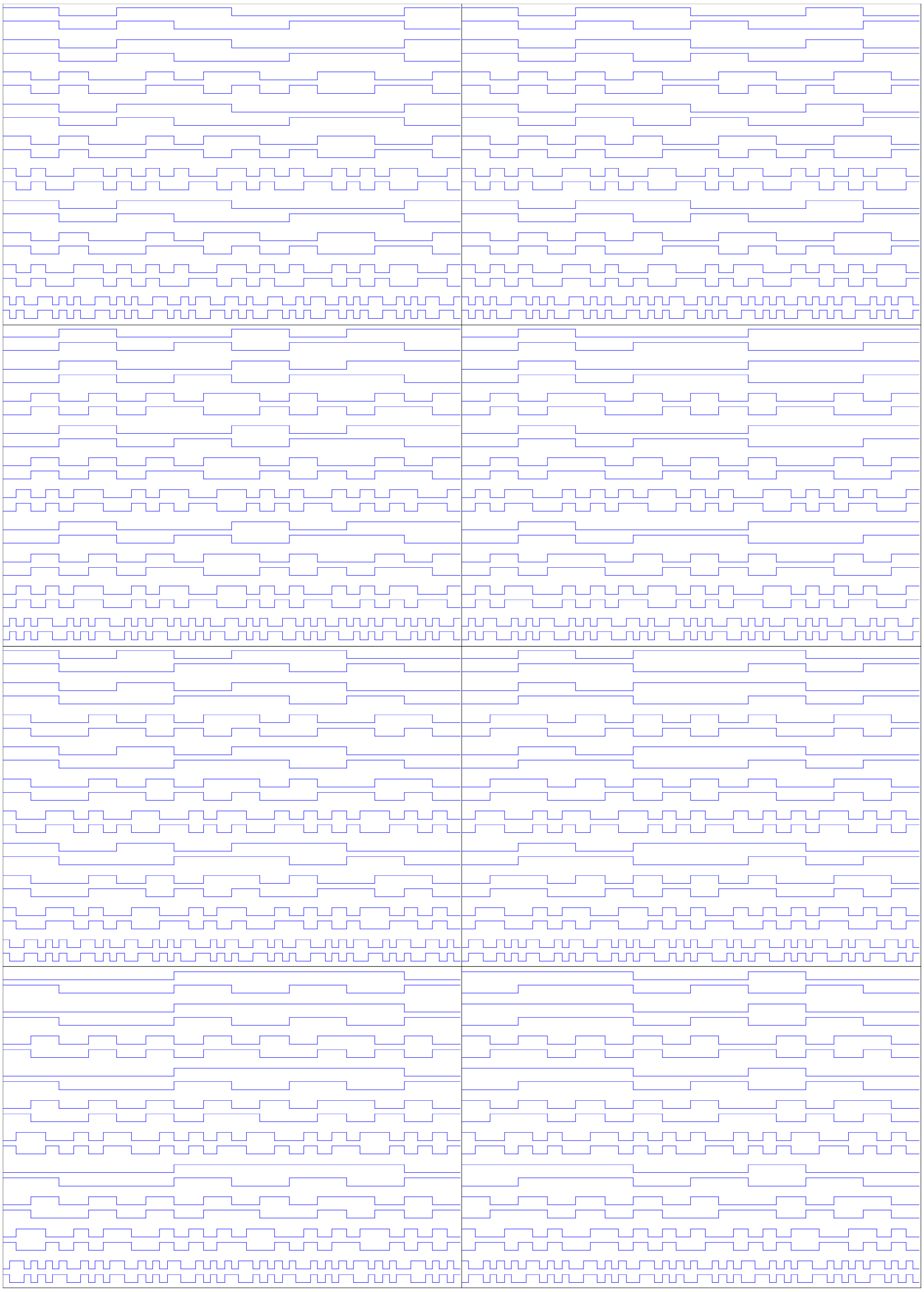

Fig. 3. The last two orthogonal basis-wise sequences for different cases of pilot symbols per frame

To obtain statistically reliable simulation of the 10 cases of pilot symbols per frame and frame length (tab. 1), it is reasonable to set $N_{\text{pack}} = 10m_{\text{err}}$. The two Hadamard orthogonal sequences to be used for the simulation are taken as they are shown in fig. 1. The two IS orthogonal sequences (in each of the eight bases) to be used for the simulation are taken as they are shown in fig. 3.

SIMULATION RESULTS

Considering the perfect orthogonality, i. e. case #1 in tab. 2, the substitution of the Hadamard sequences (fig. 1) for the IS sequences (by ISBFs in fig. 3) gives no gain. The de-orthogonalization caused by one indefinite pilot sequence symbol error (case #2) cannot be rectified by the substitution as well. The BER performance for $N_{\text{pack}} = 500000$ is shown in fig. 4 for this case, where the circled points (IS sequences for the de-orthogonalization case), and squared points (Hadamard sequences for the de-orthogonalization case) are plotted along with the dotted points (IS sequences for case #1) and asterisked points (Hadamard sequences for case #1). The BER performance for $N_{\text{pack}} = 500000$ shown in fig. 5 (with the same point markers, which will be used further) for case #3 is similar to that. Those polylines re-plotted for $N_{\text{pack}} = 250000$ for case #2 (fig. 6) and case #3 (fig. 7) are almost repeated, so the results are statistically consistent and thus reliable. The averaged BER performance for these cases are presented in fig. 8 and fig. 9, where the difference between the perfect orthogonality and de-orthogonalization is clear.

In case #4, the BER performance by the Hadamard sequences is improved by the IS sequences (fig. 10). This improvement is even more obvious for case #5 (fig. 11). Those polylines re-plotted for $N_{\text{pack}} = 250000$ for case #4 (fig. 12), and case #5 (fig. 13) are almost repeated, so the results are statistically consistent, and thus reliable. The averaged BER performance for these cases are presented in fig. 14 and fig. 15. In case #4, the BER is decreased by almost 10 % on average by using the IS sequences. In case #5, the BER is decreased by almost 16 % on average.

In case #6, the BER performance by the Hadamard sequences is improved by the IS sequences (fig. 16), although the improvement is less obvious than in cases #4 and #5. This is confirmed by re-simulating it for $N_{\text{pack}} = 250000$ (fig. 17). On average, the BER is decreased by almost 2.9 % (fig. 18).

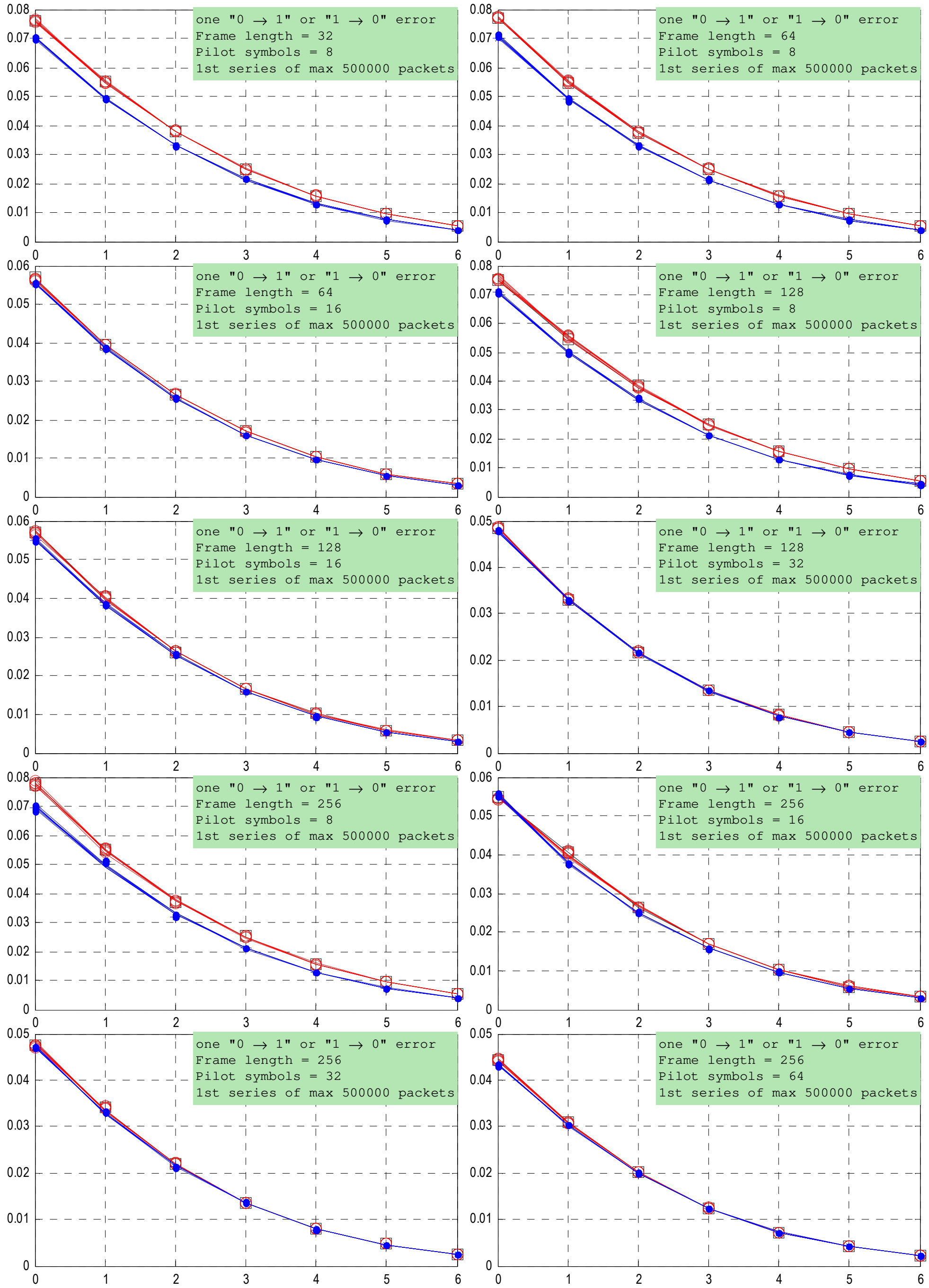

Fig. 4. The BER performance versus BENDR by one indefinite pilot symbol error de-orthogonalization ("0→1" or "1→0") for the first series of maximum 500000 packets

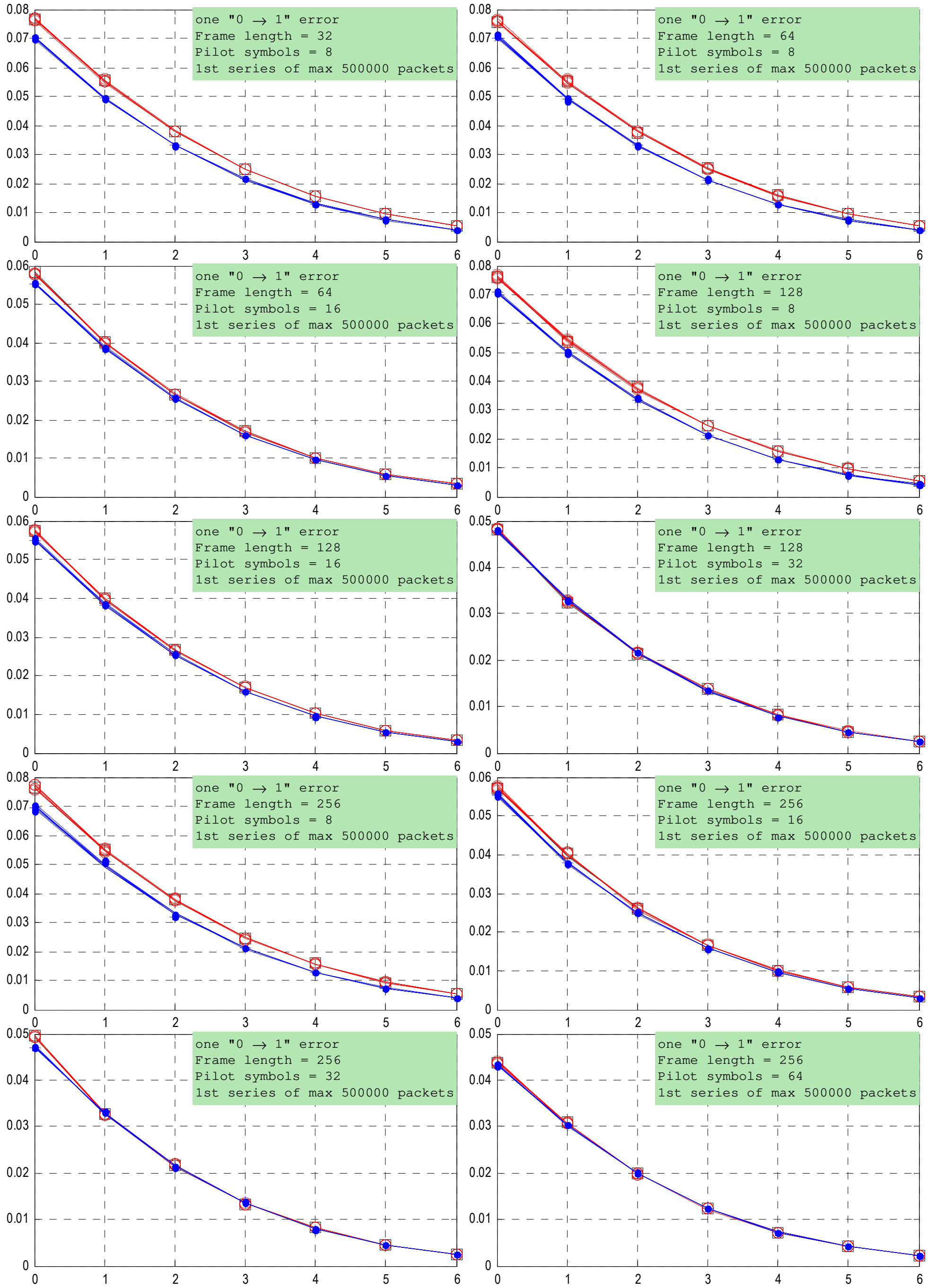

Fig. 5. The BER performance versus BENDR by one definite pilot symbol error de-orthogonalization ("0→1") for the first series of maximum 500000 packets

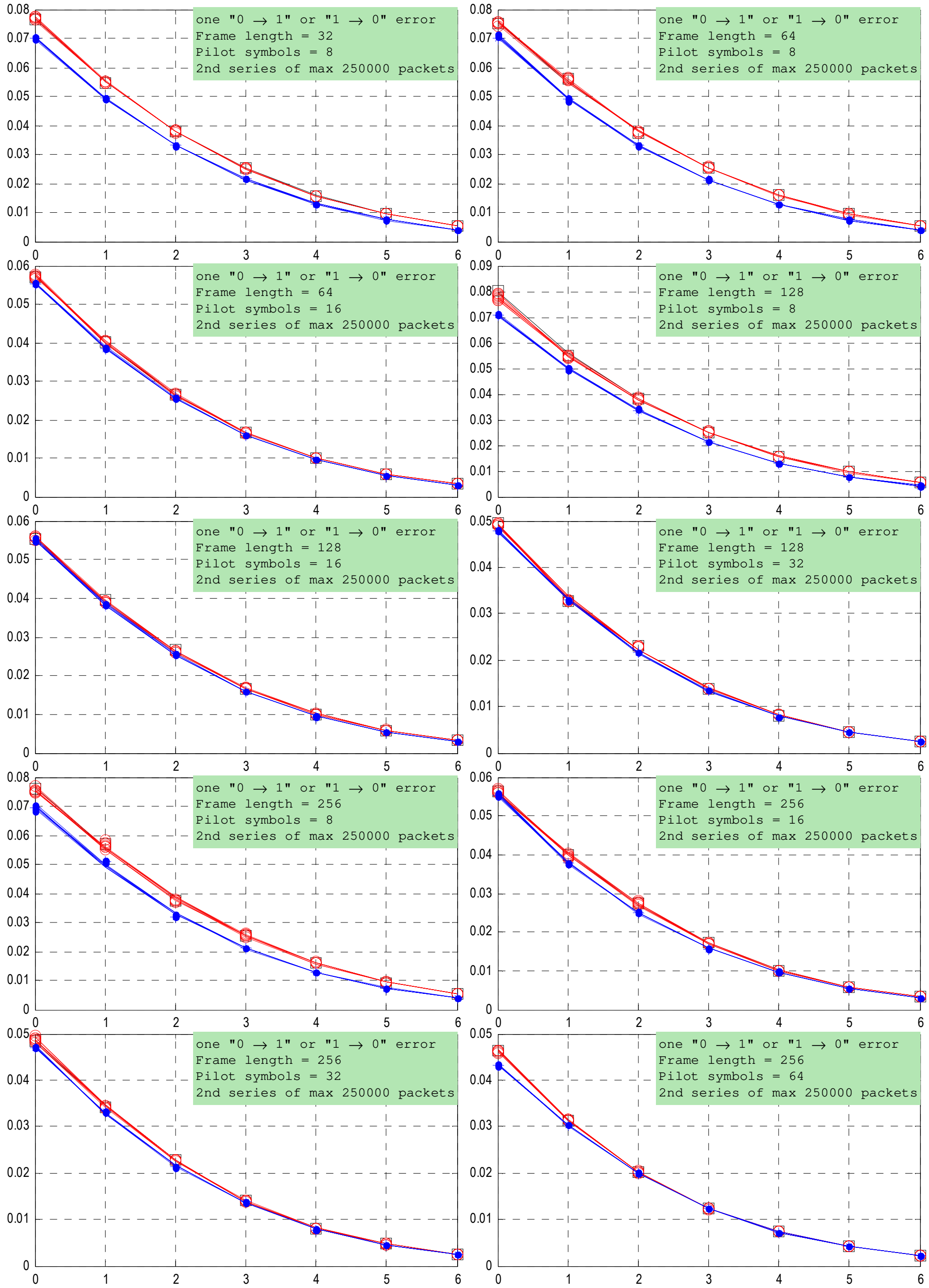

Fig. 6. The BER performance versus BENDR by one indefinite pilot symbol error de-orthogonalization (“0→1” or “1→0”) for the second series of maximum 250000 packets

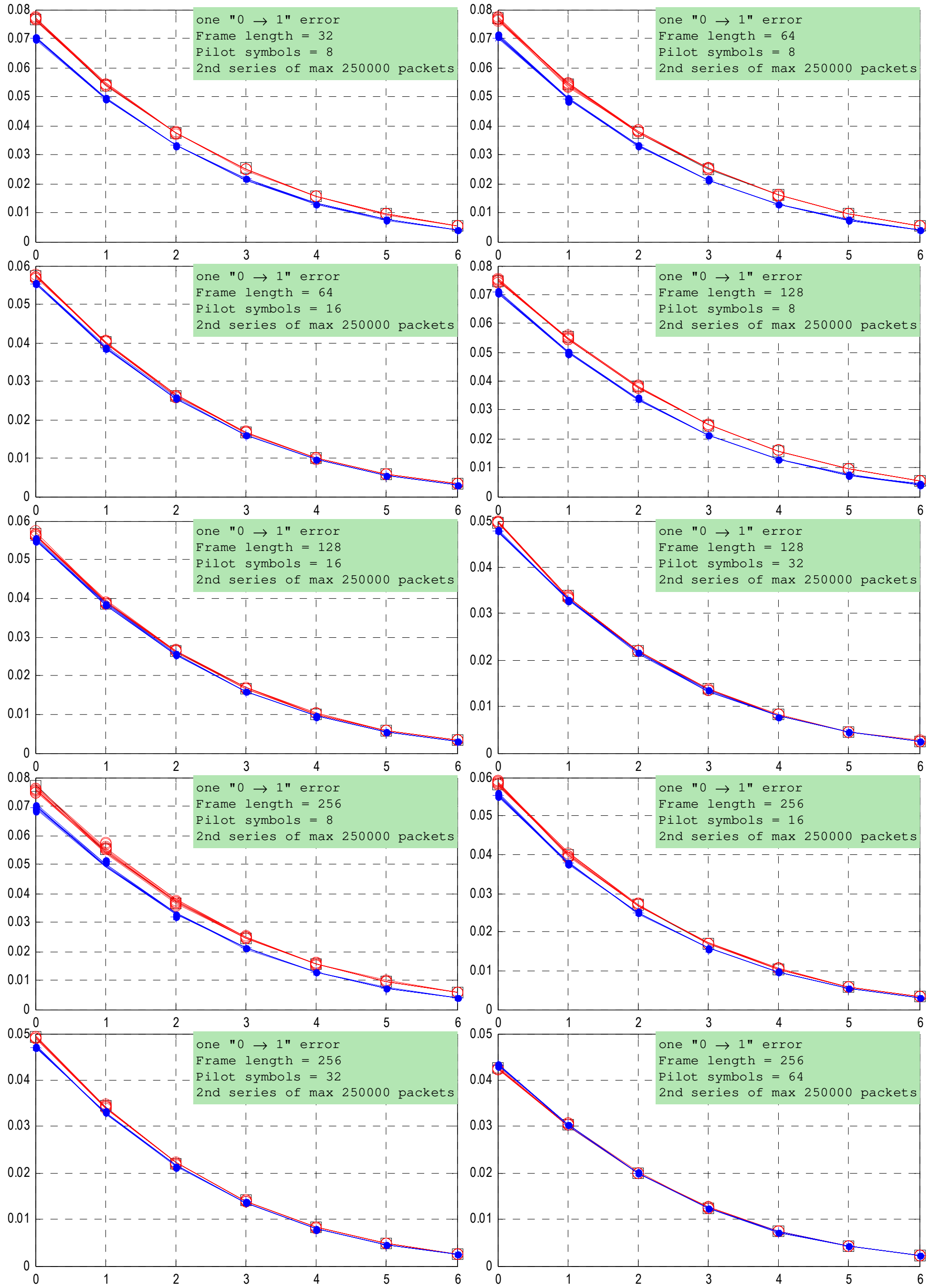

Fig. 7. The BER performance versus BENDR by one definite pilot symbol error de-orthogonalization (“0→1”) for the second series of maximum 250000 packets

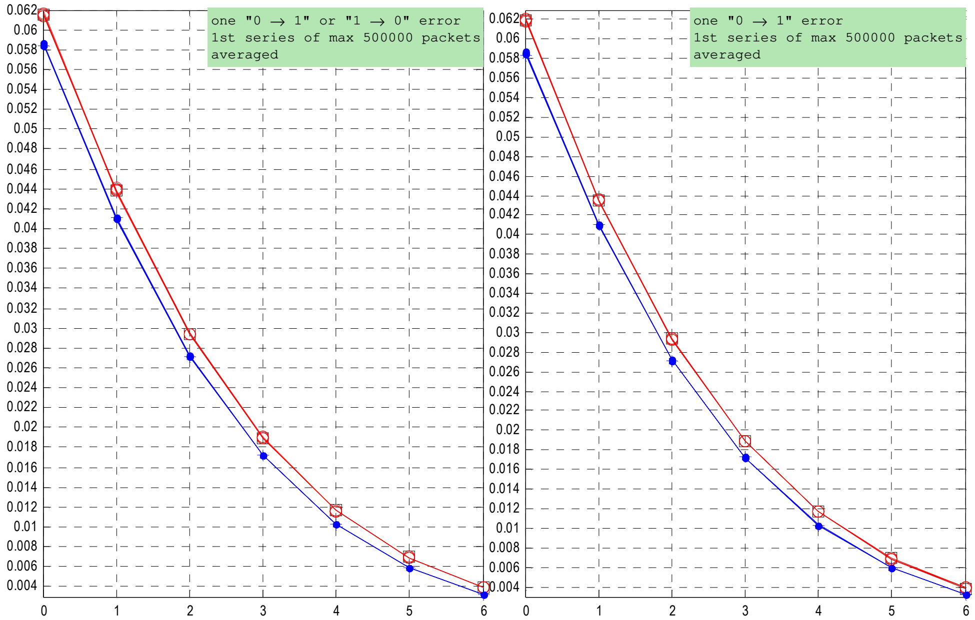

Fig. 8. The averaged BER performance versus BENDR by one pilot symbol error de-orthogonalization (cases #2 and #3) for the first series of maximum 500000 packets

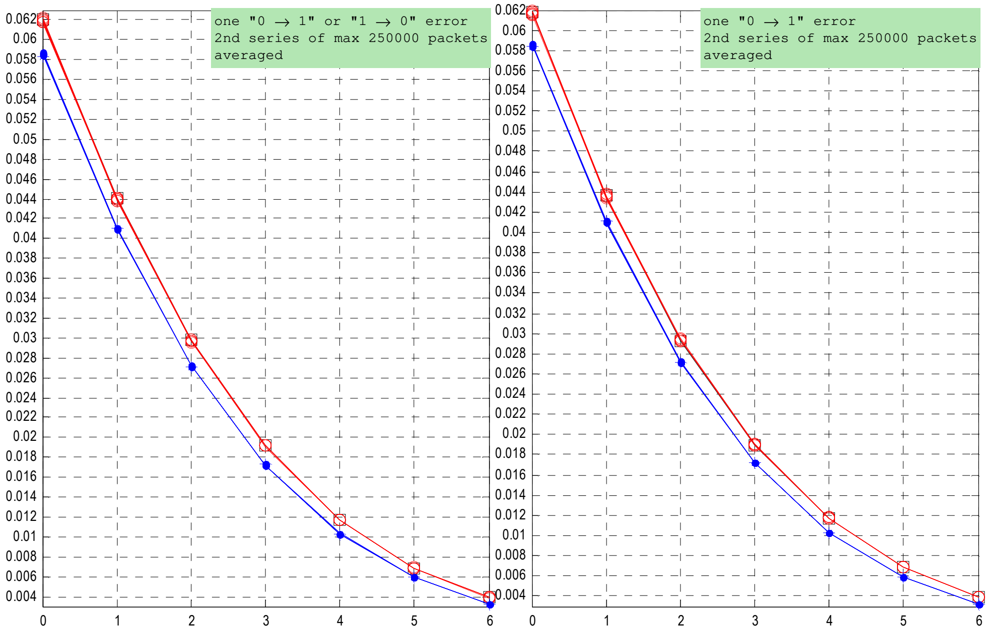

Fig. 9. The averaged BER performance versus BENDR by one pilot symbol error de-orthogonalization (cases #2 and #3) for the second series of maximum 250000 packets

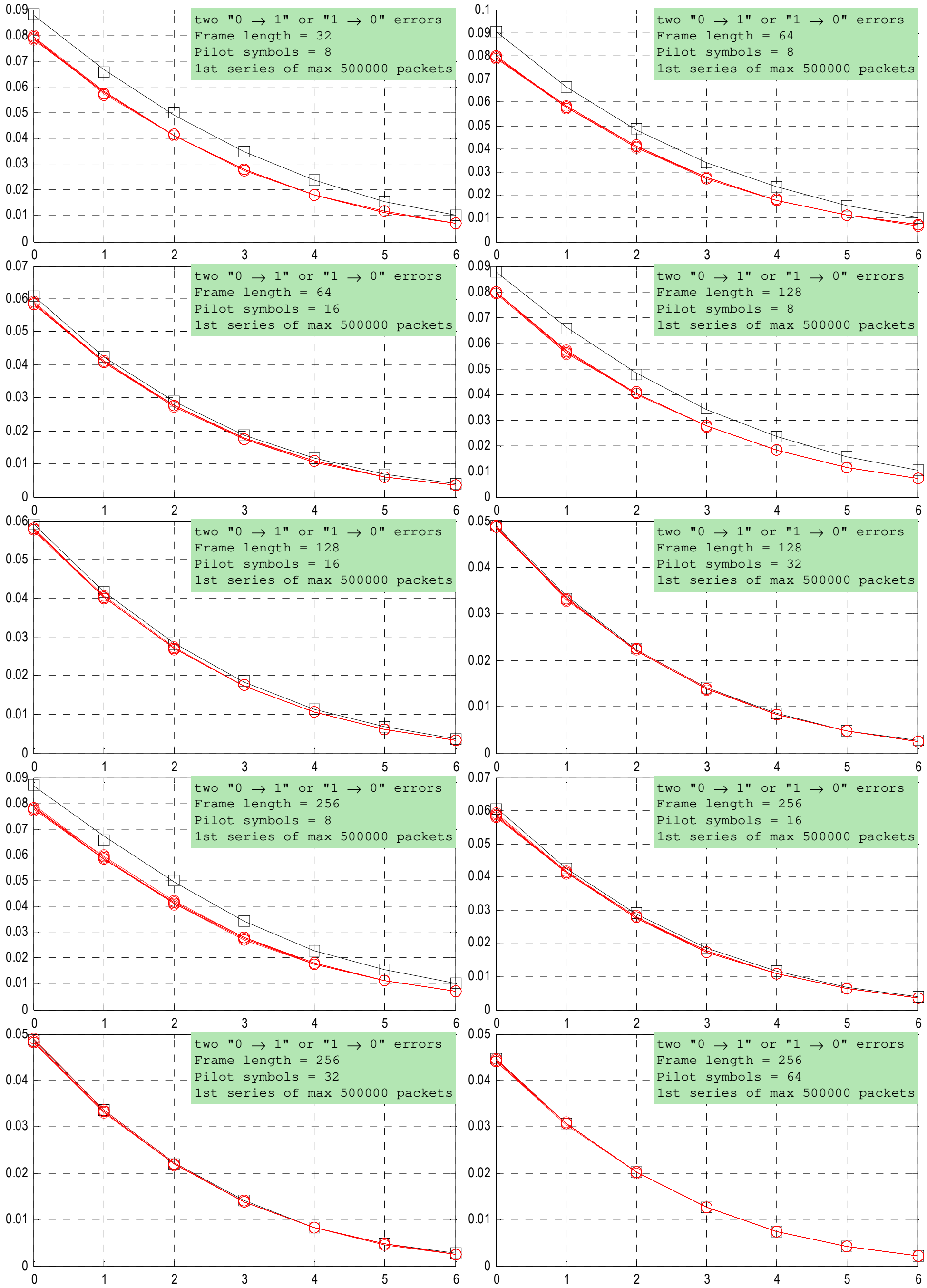

Fig. 10. The BER performance versus BENDR by two repeated indefinite pilot symbol error de-orthogonalization (twice "0→1" or "1→0") for the first series of maximum 500000 packets

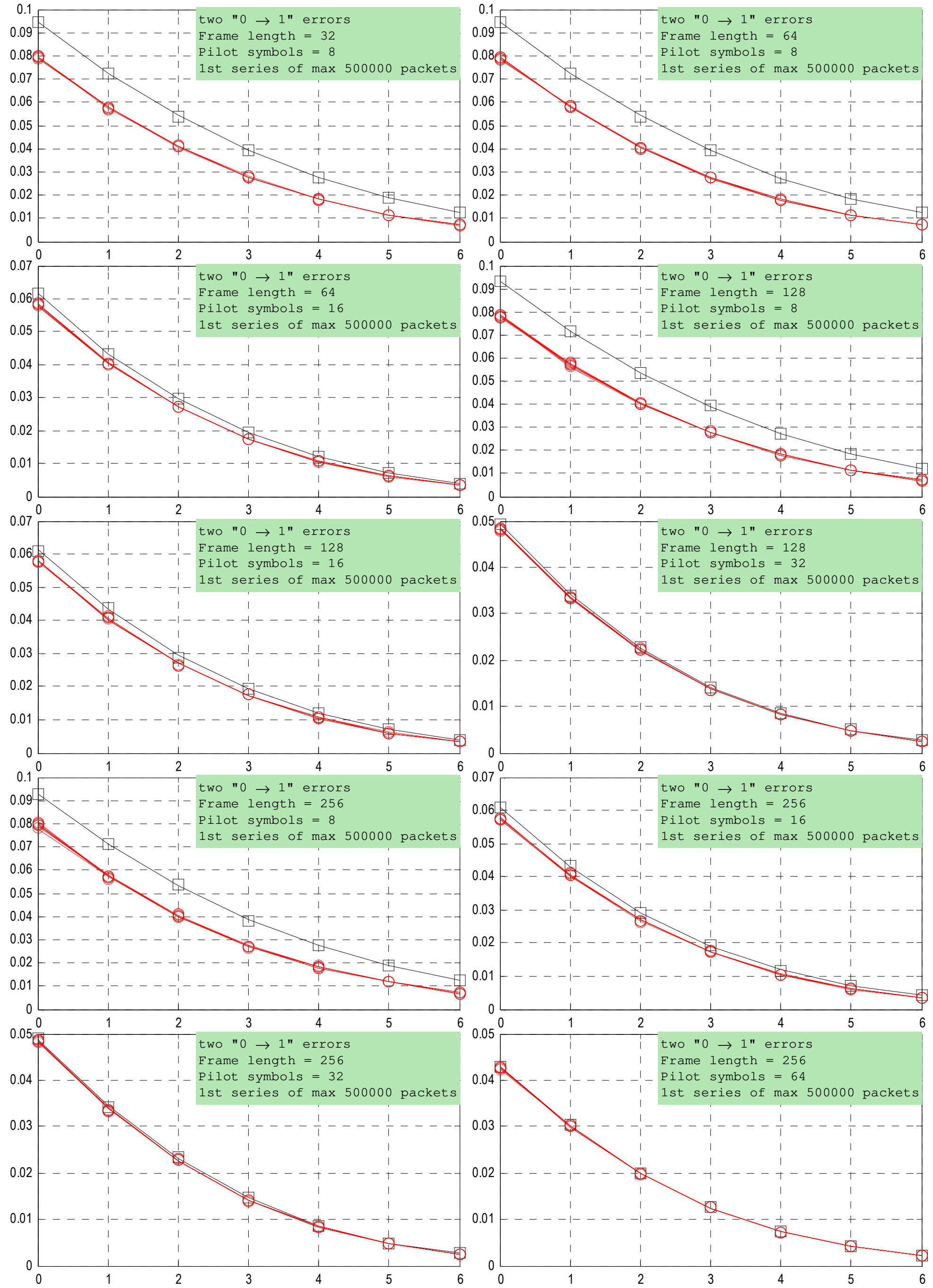

Fig. 11. The BER performance versus BENDR by two repeated definite pilot symbol error de-orthogonalization (“0→1” and “0→1”) for the first series of maximum 500000 packets

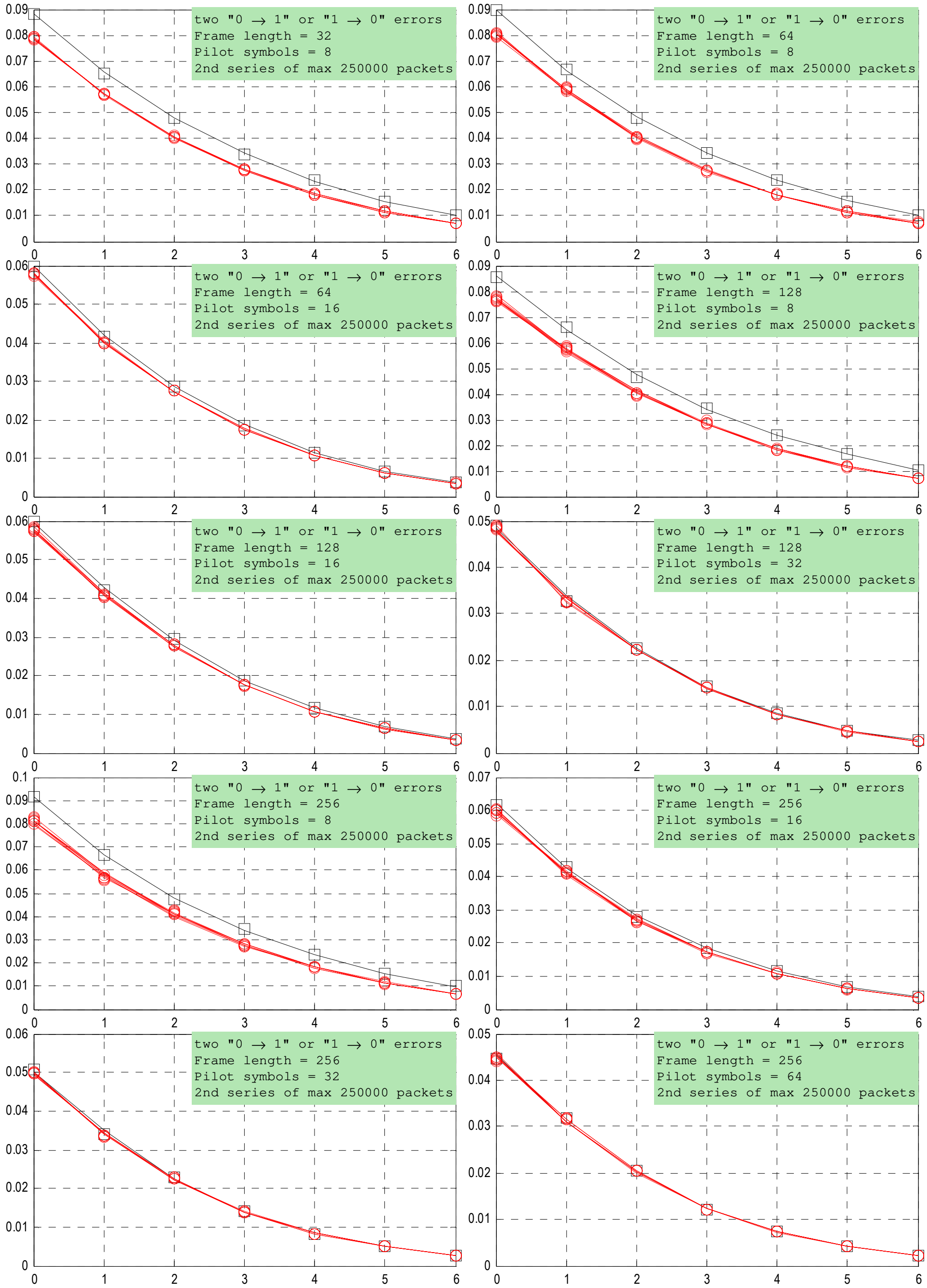

Fig. 12. The BER performance versus BENDR by two repeated indefinite pilot symbol error de-orthogonalization (twice “0→1” or “1→0”) for the second series of maximum 250000 packets

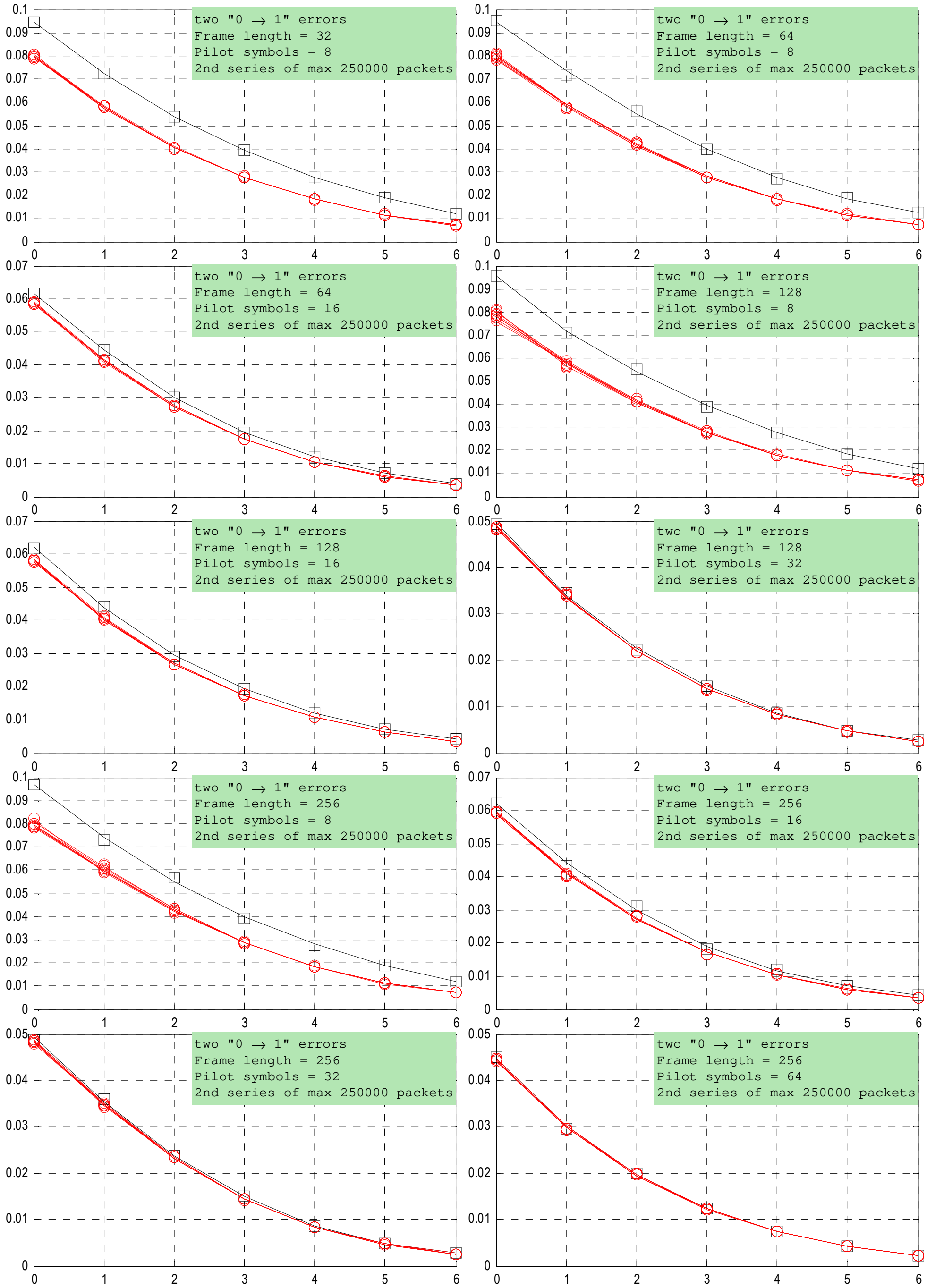

Fig. 13. The BER performance versus BENDR by two repeated definite pilot symbol error de-orthogonalization ("0→1" and "0→1") for the second series of maximum 250000 packets

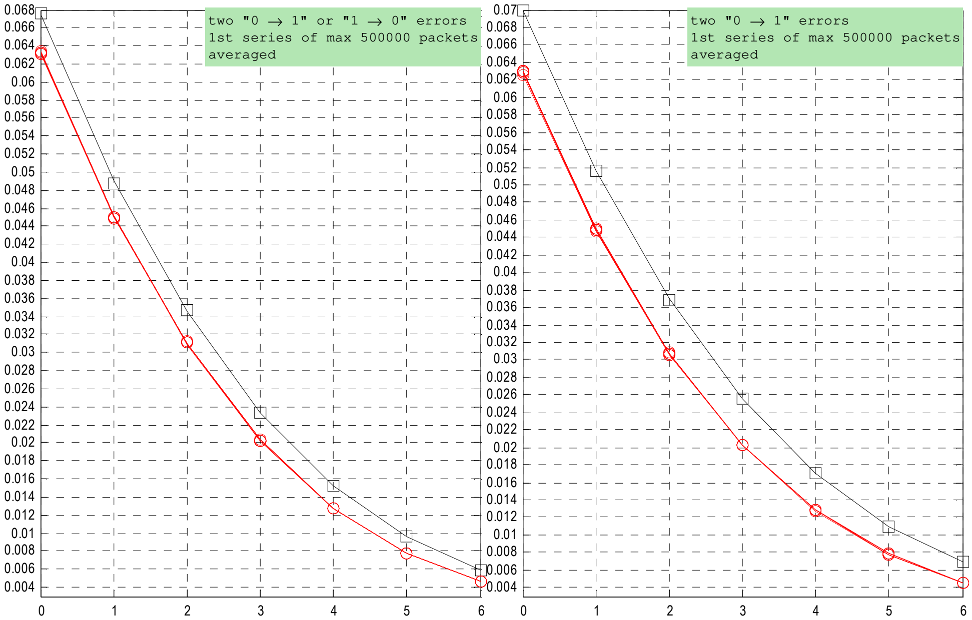

Fig. 14. The averaged BER performance versus BENDR by two repeated pilot symbol error de-orthogonalization (cases #4 and #5) for the first series of maximum 500000 packets

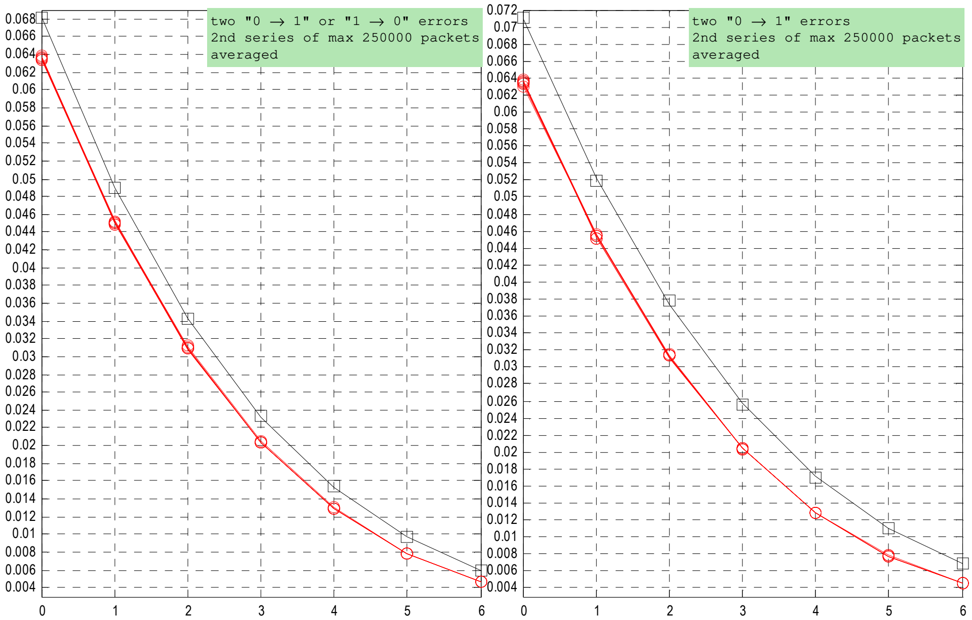

Fig. 15. The averaged BER performance versus BENDR by two repeated pilot symbol error de-orthogonalization (cases #4 and #5) for the second series of maximum 250000 packets

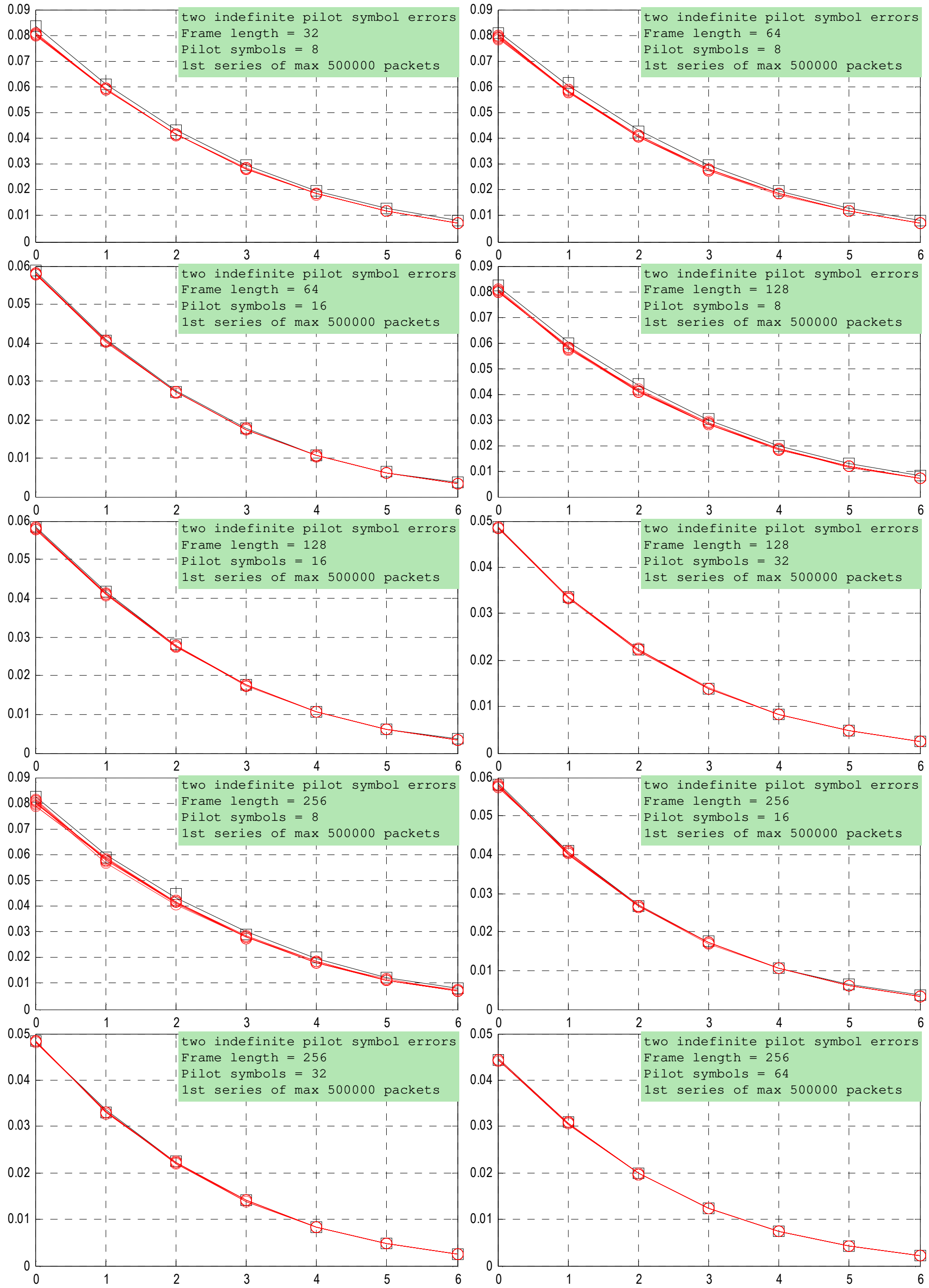

Fig. 16. The BER performance versus BENDR by two indefinite pilot symbol error de-orthogonalization for the first series of maximum 500000 packets

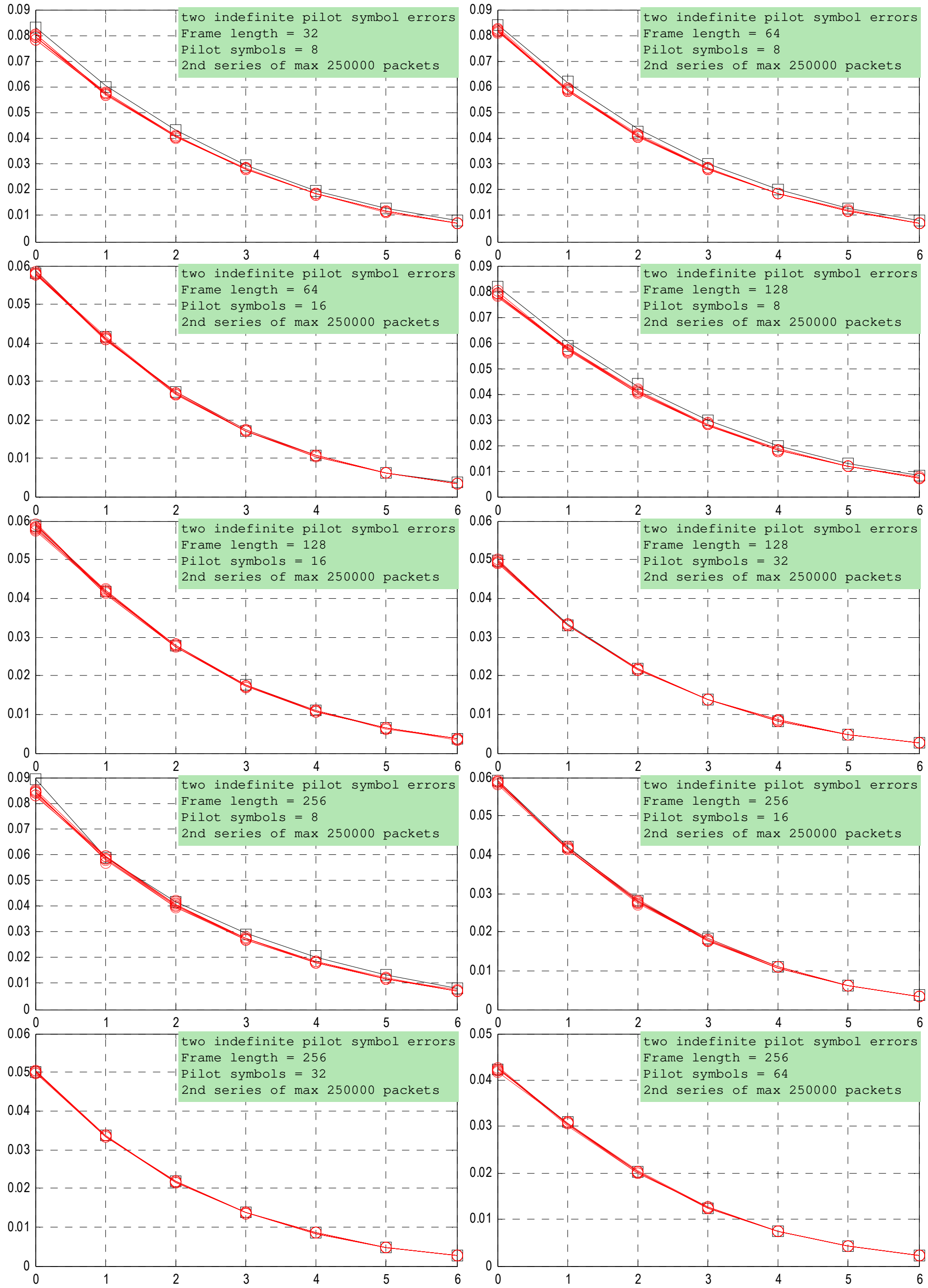

Fig. 17. The BER performance versus BENDR by two indefinite pilot symbol error de-orthogonalization for the second series of maximum 250000 packets

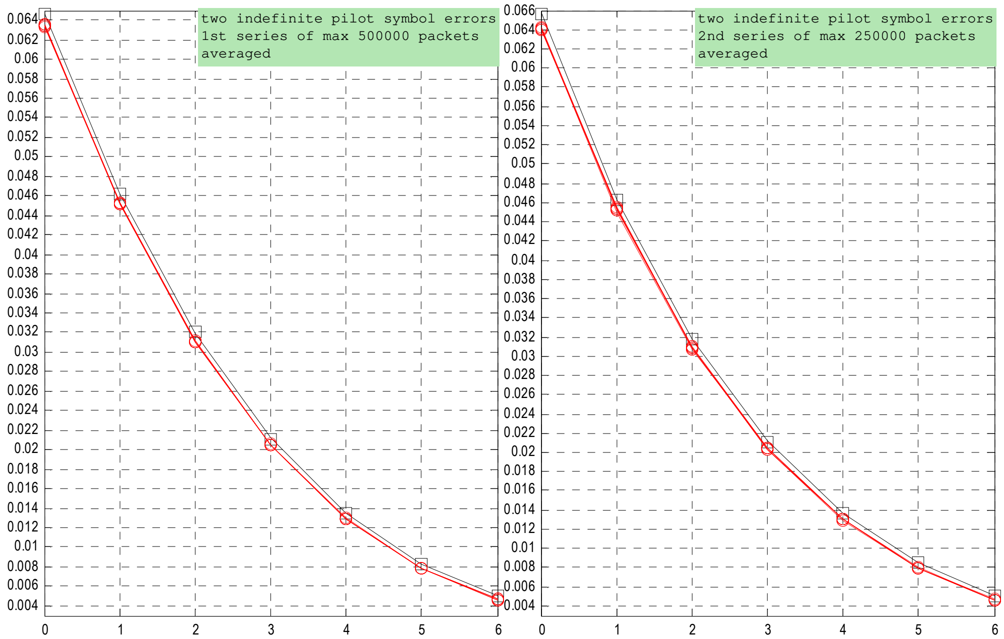

Fig. 18. The averaged BER performance by two indefinite pilot symbol error de-orthogonalization

It is worth noting, that the difference between the BER performance by the Hadamard, and IS sequences in the case of the perfect orthogonality (case #1) may exist. However, this difference is as negligible as it is for the cases (as tagged hereinbefore, cases #2 and #3) of one pilot symbol de-orthogonalization (fig. 4 – 9). In detail, the difference is not greater than 10^{-5} which is 0.033 %. The one pilot symbol de-orthogonalization still has a negative impact on the BER performance as it then impaired by 0.001 to 0.0035 (see it in both fig. 8 and fig. 9).

DISCUSSION

The polylines in fig. 4 – 7 allow seeing that the BER badly increases for the four following cases of the parameter pair of the frame length and pilot symbols per frame:

$$\{F=32, P=8\}, \{F=64, P=8\}, \{F=128, P=8\}, \{F=256, P=8\}. \qquad (1)$$

This implies that using 8 pilot symbols in 2×2 MIMO systems, even if it is 25 % of the frame length, has poor efficiency. Thus, the accuracy-versus-overhead tradeoff herein is unacceptable. Moreover, cases (1) confirm that increasing the frame length does not give necessarily a gain in the BER performance. Indeed, comparison of the respective BER polylines for cases (1) in fig. 4 – 7 reveals that they are almost unchangeable. Noticeable changes are in fig. 10 – 13, but they are not very significant. Weakly-varying polylines for cases (1) are also seen in fig. 16 and fig. 17.

Despite the one pilot symbol de-orthogonalization does have a negative impact on the BER performance, it becomes apparent only for cases (1) and, with less significance, for cases

$$\{F=64, P=16\},\ \{F=128, P=16\},\ \{F=256, P=16\}. \tag{2}$$

The one pilot symbol de-orthogonalization still increases the BER for cases

$$\{F=128, P=32\},\ \{F=256, P=32\},\ \{F=256, P=64\} \tag{3}$$

at $r_{\mathrm{Eb/No}} < 3$ dB, but it is hardly noticeable. The least BER itself is obtained for case

$$\{F=256, P=64\} \tag{4}$$

corresponding to a 2×2 MIMO system transferring long frames with a maximum information for channel estimation. This is easily confirmed by fig. 4 – 7, 10 – 13, 16, 17.

By the two repeated pilot symbol error de-orthogonalization, the BER is efficiently decreased by substituting the Hadamard sequences for the IS sequences for cases (1), that is clearly seen in fig. 10 – 13. In the case of the two repeated definite pilot symbol error de-orthogonalization, the gap between the Hadamard sequences polylines (squared points), and IS sequences polylines (circled points) is bigger. Nevertheless, it does not mean that the IS sequences are less effective in the case of the two repeated indefinite pilot symbol error de-orthogonalization. In fact, when the definite symbol is lost twice (in case #5, it is an inversion to the value of the function-constant, i. e., “0→1”), the performance by the Hadamard sequences becomes poorer than that by the IS sequences (compare fig. 10 to fig. 11, and fig. 12 to fig. 13, and also the left subplots to the right subplots in both fig. 14 and fig. 15). The gaps are significantly smaller for cases (2), in the both cases of the two repeated pilot symbol error de-orthogonalization (cases #4 and #5 in fig. 10 – 13). For cases (3), the gaps between the Hadamard sequences and IS sequences polylines are hardly noticeable (without zooming in on the respective polylines). However, some tiny gaps exist just for cases

$$\{F=128, P=32\} \text{ and } \{F=256, P=32\} \tag{5}$$

whereas there are no gaps for case (4). The same inference is made from fig. 16 and fig. 17 for the two indefinite pilot symbol error de-orthogonalization (case #6). Moreover, the polylines in the respective subplots for cases (3) do not have any difference from the respective polylines (it is better to pay attention to asterisked points) in fig. 4 – 7. Therefore, 2×2 MIMO systems transferring long frames with a maximum information for channel estimation are resistant to partial de-orthogonalization in pilot signals. The accuracy-versus-overhead tradeoff herein is likely to be acceptable.

Surely, in the realistic scenario, the pilot signal de-orthogonalization is highly probable. However, the considered de-orthogonalization cases (tab. 2) are not equiprobable. Considering only one pilot sequence symbol error, case #3 is 50 % probable. If to consider possibility of two pilot sequence symbol errors, cases #2 and #6 are complementary events. They can be counted equiprobable. Consequently, case #3 is then 25 % probable, case #4 is 25 % probable, and case #5 is then 12.5 % probable.

CONCLUSIONS

In 2×2 MIMO systems with channel estimation by the orthogonal pilot signal approach, it is possible to improve the BER performance by substituting the Hadamard sequences for the IS sequences. The improvement is estimated as a BER average decrement. The decrement is almost 10 % in the case of a de-orthogonalization caused by two repeated indefinite pilot sequence symbol errors. The probability of this case is estimated at 25 % rate. In the case of a de-orthogonalization caused by two repeated definite pilot sequence symbol errors, which is 12.5 % probable, the decrement is almost 16 %. Considering two any pilot symbol errors, whose probability is estimated at 50 % rate, the BER is decreased by almost 2.9 %.

Whichever sequences are used for piloting, the 2×2 MIMO system is resistant to the de-orthogonalization if the frame is of 128 to 256 symbols piloted with 32 to 64 symbols, respectively. The accuracy-versus-overhead tradeoff is thus optimized. A further research might be directed towards optimizing MIMO systems in which a greater number of transmit and receive antennas are employed.

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PONOWNA ORTOGONALIZACJA PO BŁĘDACH SYMBOLI PILOTUJĄCYCH W SYSTEMACH KOMUNIKACJI BEZPRZEWODOWEJ 2×2 MIMO

STRESZCZENIE

W pracy przedstawiono symulowany system komunikacji bezprzewodowej 2×2 MIMO z oszacowaniem kanału, składający się z dwóch anten nadawczych i dwóch anten odbiorczych. W procesie szacowania kanału zastosowano podejście ortogonalnego sygnału pilotującego z wykorzystaniem sekwencji Hadamarda. Na potrzeby badań symulacyjnych przyjęto modulowanie danych za pośrednictwem spójnego binarnego kluczowania z przesunięciem fazowym, podczas gdy ortogonalny podsystem kodowania bloków czasoprzestrzennych odpowiedzialny był za kodowanie informacji z wykorzystaniem kodu Alamouti. Na podstawie symulacji ustalono możliwość zmniejszenia współczynnika błędnych bitów przez zastąpienie sekwencji Hadamarda sekwencjami należącymi do ośmiu znanych baz ortogonalnych i charakteryzującymi się nieregularnymi strukturami. W przypadku deortogonalizacji wynikającej z dwóch dowolnych błędów symboli sekwencji pilotujących, współczynnik ten został zmniejszony o prawie 2.9 %. Jeśli deortogonalizacje są spowodowane przez dwa powtarzające się błędy symboli sekwencji pilotujących, nieokreślone i określone błędy uległy zmniejszeniu o odpowiednio 10 % i 16 %. Bez względu na to, które sekwencje zostały użyte do pilotowania, wykazano odporność systemu 2×2 MIMO na deortogonalizację w przypadku, gdy ramka zawierała od 128 do 256 symboli, a rozmiar sekwencji pilotującej mieścił się w zakresie od 32 do 64 symboli.

Słowa kluczowe:

komunikacja bezprzewodowa, estymacja kanału, MIMO, ortogonalne sekwencje pilotujące, współczynnik błędnych bitów.