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INFLUENCE OF DOPPLER EFFECTS ON 2×2 TO 4×4 MIMO SYSTEMS WITH DIRECT LINE-OF-SIGHT PATH BY RICIAN FADING DISTRIBUTION

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Background. For multiplying the capacity of a radio link by using multiple antennas at the transmitter and receiver ends, wireless communication networks use the MIMO technique. The quality of MIMO wireless communication may worsen when either the transmitter or receiver end is in motion, or they both are in motion. To sustain high quality of links, MIMO operates, in particular, on channel state information by using orthogonal pilot sequences.

Objective. The goal is to estimate the bit-error-rate performance of 2×2, 3×3, and 4×4 MIMO systems with orthogonal pilot sequences for a range of Doppler shifts by the Rician fading distribution modeling the scenario of direct line-of-sight path. The estimation is believed to answer the question on MIMO efficiency by ascertaining whether increasing the number of antennas mitigates the Doppler effect in 2×2 to 4×4 MIMO systems with direct line-of-sight path.

Methods. To achieve the goal, 2×2 to 4×4 MIMO systems with channel state estimation are simulated. The simulation is configured and carried out by using MATLAB® R2019a Communications System Toolbox™ functions. The 35 subcases of the frame length and number of pilot symbols per frame are considered.

Results. The near-exponential-type decreasing of the bit-error-rate performance is almost not violated by no motion, whereas further speed increments destroy it for 2×2 MIMO systems. It is revealed that too long packet transmissions by short orthogonal pilot sequences (with respect to the packet length) are prone to errors. This especially concerns 2×2 MIMO systems, where channel state estimation by short orthogonal pilot sequences appears to be ineffective or weakly effective.

Conclusions. In general, to maintain an appropriate MIMO link data rate, the packet length should be shortened as the motion speed increases. Increasing the number of antennas additionally mitigates Doppler effects. So, 4×4 MIMO system transmissions are indeed efficient. The shortest possible packet transmissions are not affected by Doppler effects if three or four antennas are used.

Keywords: wireless communication system; MIMO; Rician fading; channel state estimation; orthogonal pilot sequences; Doppler effect.

1. Rician fading distribution and orthogonal piloting in MIMO

As of 2020, 5G networks in Ukraine are the most promising wireless communication technology. They are still being tested before becoming country-widespread. For multiplying the capacity of a radio link by using multiple antennas at the transmitter and receiver ends, 5G networks use the MIMO technique and massive MIMO approach [1]. The quality of MIMO wireless communication, however, may worsen when either the transmitter or receiver end is in motion, or they both are in motion [2], [3]. This is caused by the multipath scattering and Doppler effects [1], [3], [4]. Nevertheless, it may seem that a scenario of direct line-of-sight path from transmitter to receiver (DLoSPTR) by city traffic speeds should not have bad influence on the quality. This is so due to the scenario of DLoSPTR by human-walking speeds or vehicular speeds up to 60 km/h is believed to result in weak Doppler shifts and negligible path delays without reflections. DLoSPTR is modeled by Rician fading distribution [2], [5].

To sustain high quality of links, MIMO operates, in particular, on channel state information [1, 4, 6]. The channel state information is extracted from the received signal by using orthogonal pilot signals prepended to every packet [7]. Although the orthogonal pilot signal approach (OPSA) for channel state estimation (CSE) has a higher overhead, it achieves a better channel estimation accuracy than without any known transmitted sequence [8]. Thus, Doppler shifts and combined effects of scattering, fading, and power decay with distance are compensated by CSE.

Obviously, longer orthogonal pilot sequences (OPSs) are expected to ensure better MIMO performance. Nevertheless, OPSs cannot be too long as the OPS length is limited by the coherence time of the channel [9]. Besides, the reuse of OPSs of several co-channel cells leads to pilot contamination worsening the MIMO performance [10].

In MIMO, the first OPS is usually the sequence of ones, which is the Walsh function of the zeroth order (being a function-constant) [11]. The second OPS, in the given finite binary basis ordered by Walsh [11],

[12], is the Walsh function of the last order. This function is an ideal meander of the highest frequency [12]. If to consider Walsh functions from the middle of the unit interval on which they are defined, the structure of Walsh functions is symmetrical [11], [12]. Partially unsymmetrical binary functions (PUBFs) which constitute orthogonal bases are known also (e. g., see [13], [14]). The eight orthogonal bases of such PUBFs (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 [12] were simulated to substitute the respective Walsh functions in wireless communication systems with the code division multiple access [15]. It was shown in [12] and [14] that these orthogonal sets of binary functions outperform a Walsh set, where the bit-error rate (BER) is decreased by 3 % to 5 %. Thus, it is thereafter assumed that BER in MIMO systems with OPSA by DLoSPTR might be decreased by using the similar substitution. This is believed to increase general throughput and reliability of MIMO links, i. e., to further develop 5G networks.

2. Goal formulation

The goal is to estimate the BER performance of 2×2, 3×3, and 4×4 MIMO systems with CSE by the OPSA for both the Walsh (Hadamard) and Romanuke binary functions for a range of Doppler shifts by the Rician fading distribution (modeling the scenario of DLoSPTR) [2], [5]. For this, various relationships of the frame length and pilot symbols per frame will be considered. The estimated BER performance is believed to answer the question on MIMO efficiency by ascertaining whether increasing the number of antennas mitigates the Doppler effect by DLoSPTR. A possibility of CSE by the OPSA by more appropriate orthogonal sets is to be studied as well.

To achieve the said goal, 2×2 to 4×4 MIMO wireless communication systems with CSE will be simulated, where the number of transmit and receive antennas is the same (two, three, and four, respectively). The simulation will be configured and carried out by using MATLAB® R2019a Communications System Toolbox™ (CST) functions. The BER performance is to be plotted versus a ratio of bit energy to noise power spectral density. The range of the bit-energy-to-noise-density ratio (BENDR) is set from 0 dB to 8 dB with a step of 1 dB. The range of Doppler shifts is from zero to a value at which the motion achieves city traffic speeds.

3. Simulation parameters and set-up

In the MATLAB® CST simulation, the data are modulated and encoded as follows. For using 2 to 4 transmit antennas, the signal is modulated by applying the quaternary phase shift keying (QPSK) method. In the MATLAB® CST, this is realized by the QPSKModulator object. The modulated signal is then encoded by using the OSTBCEncoder object. The OSTBCEncoder object encodes an input symbol sequence using orthogonal space-time block code (OSTBC). The block maps the input symbols block-wise and concatenates the output codeword matrices in the time domain.

While the modulated signal is encoded, the symbol rate of the code is 1 for a 2×2 MIMO system, and is 3/4 for 3×3 and 4×4 MIMO systems [1], [9]. To match the symbol rate with piloting, the frame length denoted by F is set at

$$F = 36 \cdot 2^n \text{ by } n = \overline{0, 7} \qquad (1)$$

symbols. Subsequently, the number of pilot symbols per frame denoted by P, which commonly does not exceed 25 % of the frame length, is set at

$$P = 2^{n+3} \text{ by } n = \overline{0, 6} \qquad (2)$$

symbols, with respect to each frame length (Table 1). This results in the 35 subcases of the two parameters paired for simulation.

Table 1. The 35 subcases of the frame length and number of pilot symbols per frame by (1) and (2)

F	36	72	72	144	144	144	288
P	8	8	16	8	16	32	8
F	288	288	288	576	576	576	576
P	16	32	64	8	16	32	64
F	576	1152	1152	1152	1152	1152	1152
P	128	8	16	32	64	128	256
F	2304	2304	2304	2304	2304	2304	2304
P	8	16	32	64	128	256	512
F	4608	4608	4608	4608	4608	4608	4608
P	8	16	32	64	128	256	512

OPSs are formed as follows. In an $N \times N$ MIMO system, the N pilot sequences are taken as the first N Walsh Hadamard-ordered functions from the basis of P functions (see an example in Fig. 1). In the case of using orthogonal codes by PUBFs [12], [13], the N pilot sequences are taken as the last N binary functions from each of the eight bases of P functions (see an example in Fig. 2).

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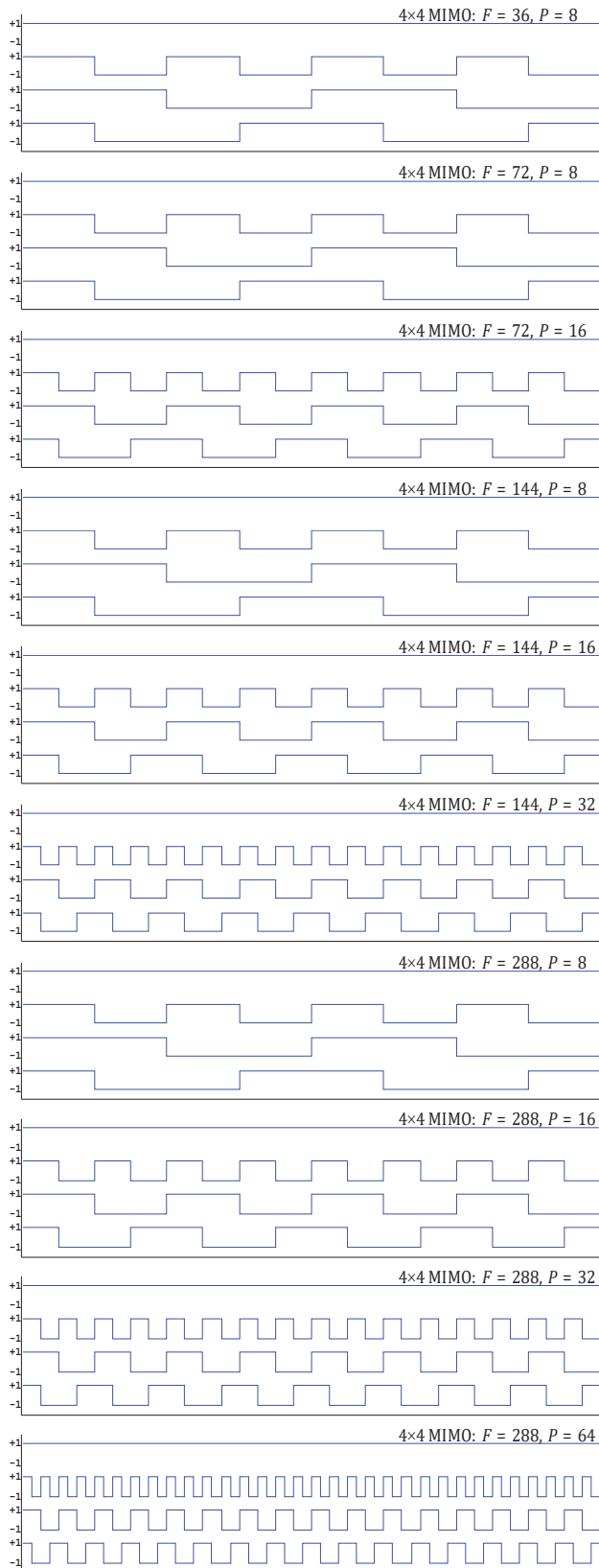
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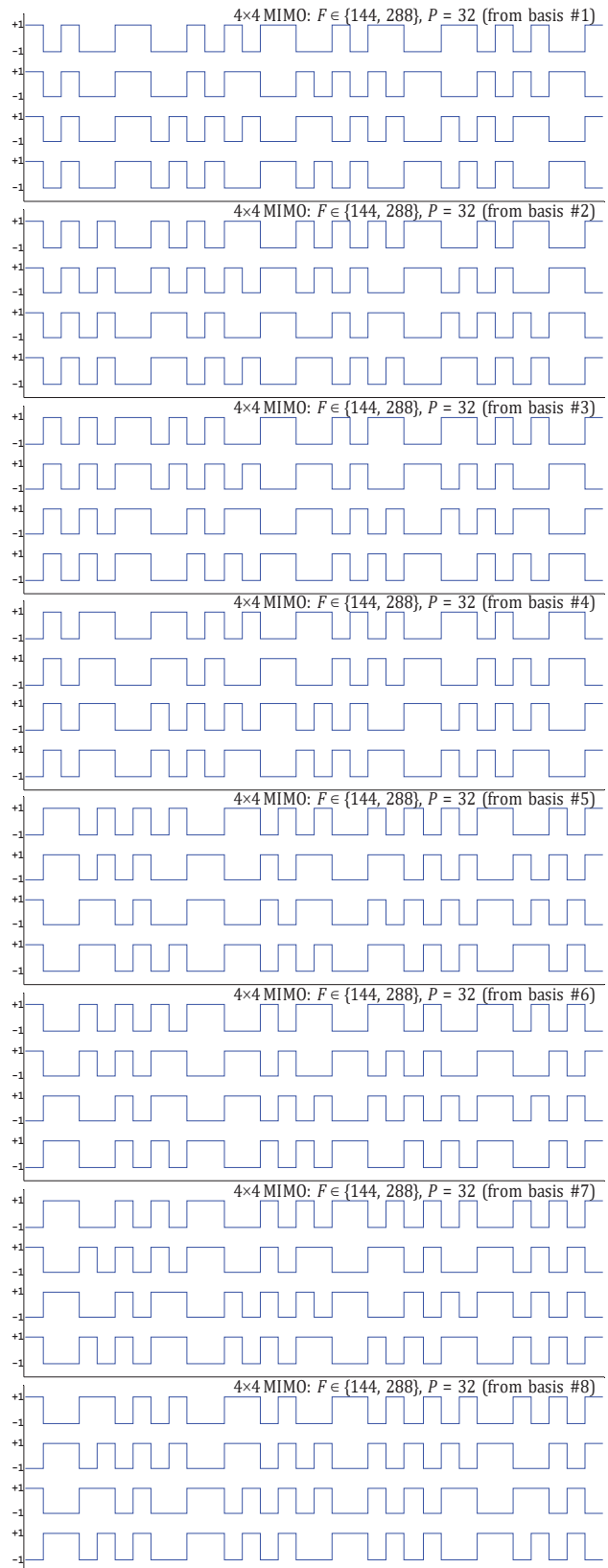Fig. 1. The four Walsh Hadamard-ordered orthogonal functions in a 4×4 MIMO system

Fig. 2. The four last PUBFs (from each of the eight bases) in a 4×4 MIMO system

For each of those 9 BENDR points (from 0 dB to 8 dB with a step of 1 dB), maximum 5000 packets (this amount is sufficient to achieve statistical stability of simulation results) are transmitted through flat-fading Rician channels [5], to which white Gaussian noise is added by applying the CST AWGNChannel object. It is assumed that the channel remains unchanged for the length of the packet (i. e., it undergoes slow fading). Besides, it is additionally assumed that the channel undergoes independent fading between the multiple transmit-receive antenna pairs [16].

At the receiving end, the signal is combined and demodulated. For this, the CST OSTBCCombiner object combines the signals from all of the receive antennas and the channel estimate signal to extract the soft information of the symbols encoded by an OSTBC. The combining algorithm uses only the estimate for the first symbol period per codeword block. The output of the combiner is demodulated by applying the CST QPSKDemodulator object. While an end-to-end MIMO system is simulated, the number of errors is registered for every BENDR point at each Doppler shift (including no motion, i. e. by zero Doppler shift) for every subcase in Table 1. The maximum number of errors is 10 % of the maximum number of packets. So, if 500 errors occur at a given BENDR, the simulation loop for the given BENDR is broken.

Denote the speed of the motion by $\tilde{v}$ and the Doppler shift measured in Hz by S_{Doppler}. If f_{carrier} is the carrier frequency in GHz, then speed $\tilde{v}$ measured in km/hr is expressed via S_{Doppler} and f_{carrier} as [3]

$$\tilde{v} = \frac{1.08 \cdot S_{\text{Doppler}}}{f_{\text{carrier}}}. \qquad (3)$$

So, at the same Doppler shift, lesser carrier frequencies correspond to faster motion. Thus, if $f_{\text{carrier}} = 2.4$ GHz and the speed is $\tilde{v} = 45$ km/hr (which is close to a medium city traffic speed), the Doppler shift is 100 Hz. If $f_{\text{carrier}} = 5.9$ GHz, shift $S_{\text{Doppler}} = 100$ Hz builds up at about $\tilde{v} = 18.3$ km/hr. A city traffic speed of almost 55 km/hr by such a carrier corresponds to a Doppler shift in 300 Hz.

4. Visualization of the simulation results

For a benchmark, the BER performance versus BENDR by no motion with pairs $\{F, P\}$ is plotted in Fig. 3, where Hadamard sequences are marked with squared points and the PUBF orthogonal sequences are marked with circled points. The polylines for a MIMO system with a greater number of transmit-receive antenna pairs are visualized thicker. The same markers

and line thickness will be used further. Fig. 3 shows that, except for the six subcases of

$$\{F = 2304, P = 8\}, \qquad (4)$$

$$\{F = 4608, P = 8\}, \qquad (5)$$

$$\{F = 4608, P = 16\}, \qquad (6)$$

$$\{F = 4608, P = 32\}, \qquad (7)$$

$$\{F = 4608, P = 64\}, \qquad (8)$$

$$\{F = 4608, P = 128\}, \qquad (9)$$

and the subcase of

$$\{F = 144, P = 8\}, \qquad (10)$$

the polylines for 2×2 MIMO systems are distinctly above the polylines for 3×3 MIMO systems, and the latter are above the polylines for 4×4 MIMO systems. This means that the best performance by no motion is achieved by increasing the number of transmit-receive antenna pairs by the exception of either transmitting very long packets ($F = 4608$, in the bottom subplot row) or long packets having too short OPSs in the subcase of (4). In the subcase of (10), the polylines for 3×3 and 4×4 MIMO have unexpectedly intersected due to probably a significant amount of errors registered at a BENDR of 0 dB. The least BER is obtained by transmitting longer packets with the longest OPSs. In particular, this is the subcases of

$$\{F = 2304, P = 512\}. \qquad (11)$$

At a Doppler shift of $S_{\text{Doppler}} = 100$ Hz, the BER performance undergoes significant changes (Fig. 4). This mainly concerns both transmitting long packets with too short OPSs and transmitting very long packets (whichever they are piloted): in the 20 subcases of

$$\{F = 288, P = 8\}, \qquad (12)$$

$$\{F = 576, P = 8\}, \qquad (13)$$

$$\{F = 576, P = 16\}, \qquad (14)$$

$$\{F = 1152, P = 8\}, \qquad (15)$$

$$\{F = 1152, P = 16\}, \qquad (16)$$

$$\{F = 1152, P = 32\}, \qquad (17)$$

subcase (4) and the remaining six subcases by $F = 2304$ (the second subplot row from the bottom), and all the subcases by $F = 4608$ (the bottom subplot row), the BER distinctly worsens. On the other hand, transmissions by
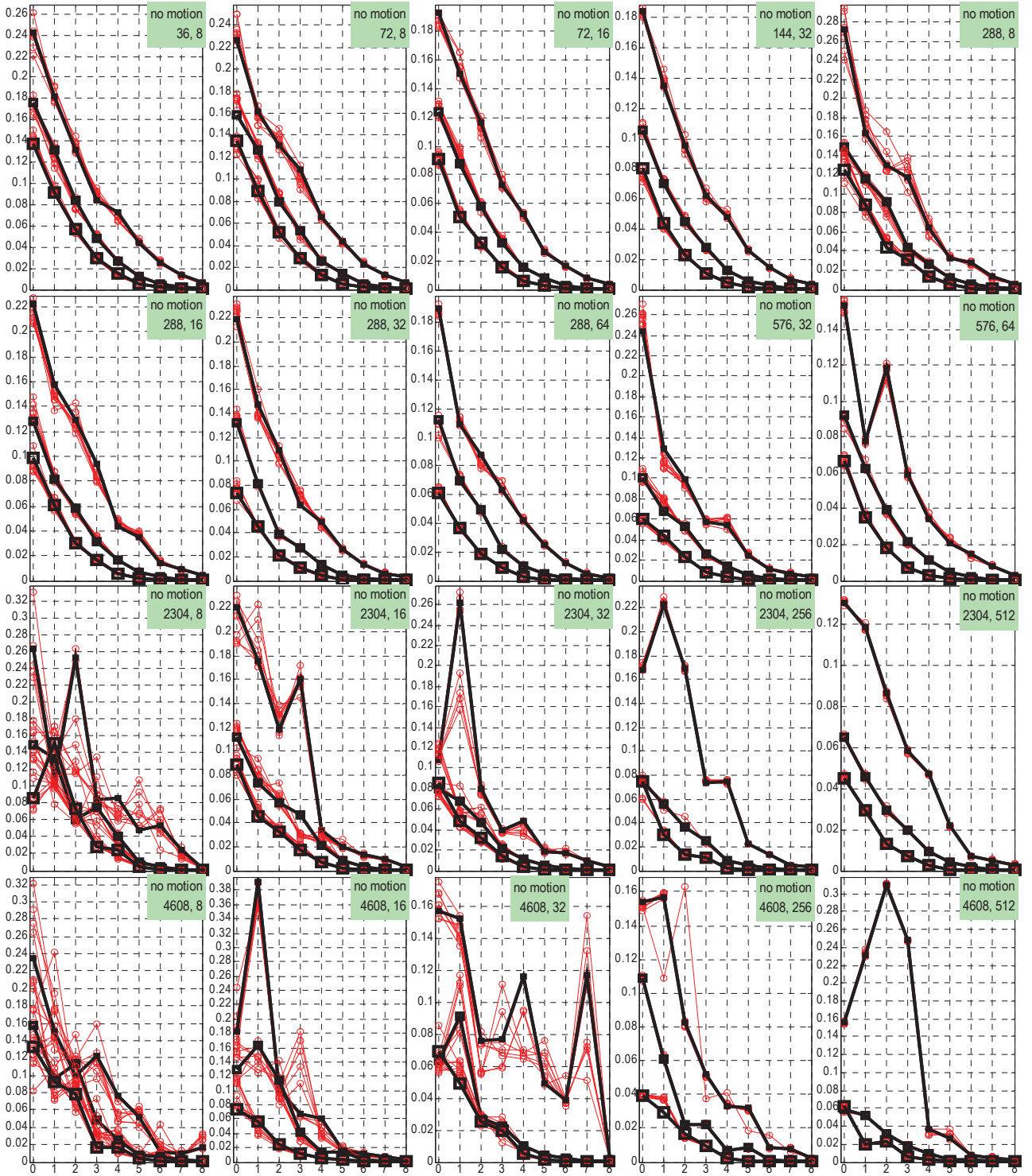
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Fig. 3. The BER performance versus BENDR by no motion

$$\{F = 32, P = 8\}, \tag{18}$$

$$\{F = 144, P = 32\}, \tag{19}$$

$$\{F = 288, P = 32\}, \tag{20}$$

$$\{F = 288, P = 64\}, \tag{21}$$

$$\{F = 576, P = 128\} \tag{22}$$

are almost unaffected by this Doppler shift. However, 2×2 MIMO transmissions are more prone to the Doppler effect even by the subcases of (18) — (22).

Obviously, the BER performance undergoes further worsening at a Doppler shift of $S_{\text{Doppler}} = 200$ Hz (Fig.

5). Using relationship (3), this corresponds to the motion with speeds between roughly 36 and 90 km/hr. At such speeds, MIMO transmissions of long packets are hardly practicable even at high BENDRs (see the two bottom rows). Transmissions by (17) and

$$\{F = 1152, P = 64\}, \tag{23}$$

$$\{F = 1152, P = 128\}, \tag{24}$$

$$\{F = 1152, P = 256\} \tag{25}$$

are practicable only for 4×4 MIMO systems. Meanwhile, transmissions by (18) — (21),
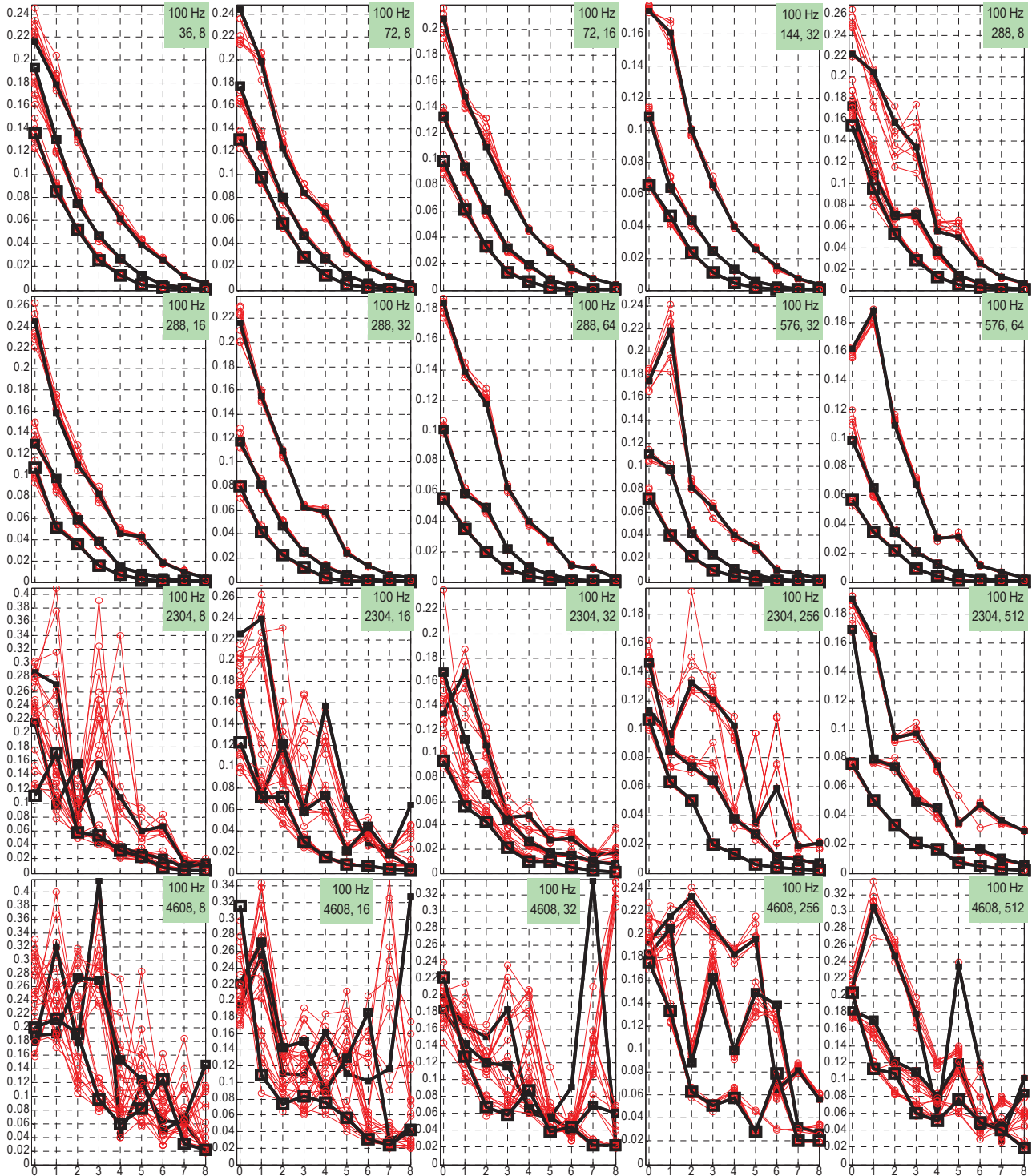
$$\{F = 576, P = 64\} \tag{26}$$

Fig. 4. The BER performance versus BENDR by a 100 Hz Doppler shift

and (22) are almost unaffected by this Doppler shift.

Figure 6 presents the BER performance in an ultimate case, when the motion speed varies between 55 (by $f_{\mathrm{carrier}} = 5.9$ GHz) and 135 km/hr (by $f_{\mathrm{carrier}} = 2.4$ GHz). Evidently, Fig. 6 fairly reveals

that transmissions by medium ($F = 1152$) and long packets are impaired unless BENDR reaches 8 dB for 4×4 MIMO systems. Meanwhile, short packet transmissions by (18) — (21) are still unaffected by such motion speeds.
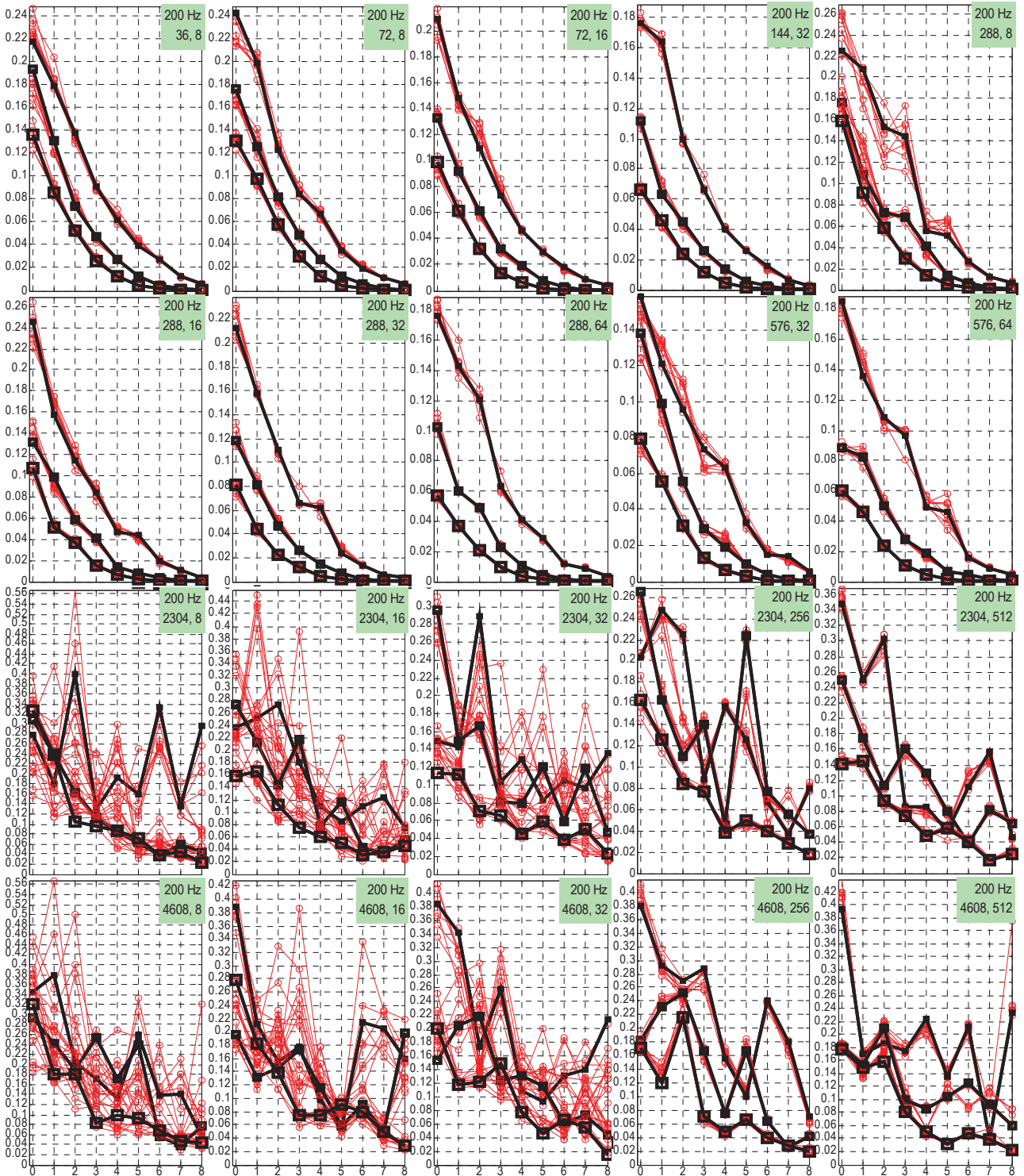

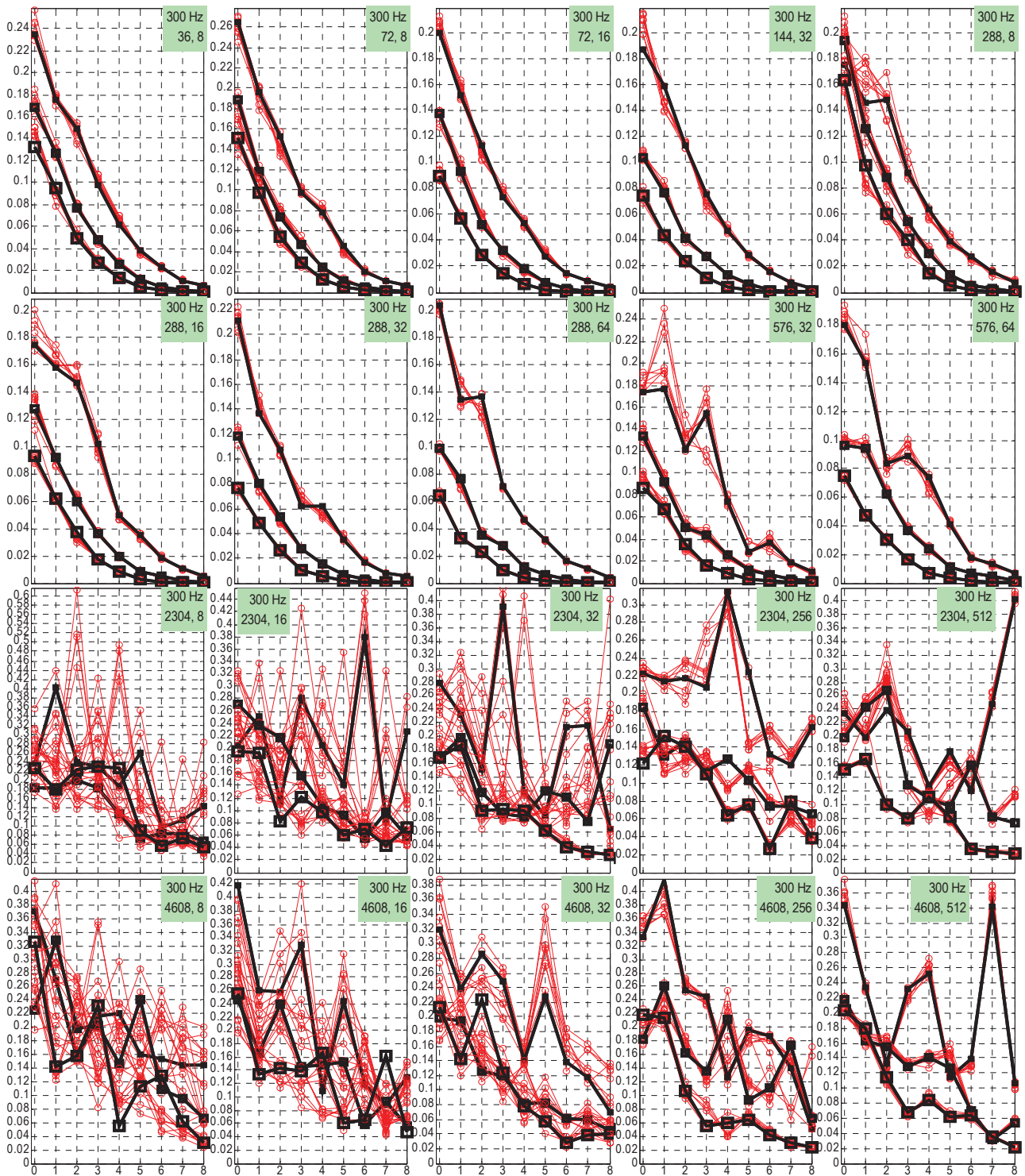Fig. 5. The BER performance versus BENDR by a 100 Hz Doppler shift

Fig. 6. The BER performance versus BENDR by a 100 Hz Doppler shift

The averaged BER performance versus BENDR shown in Fig. 7 confirms that even city traffic speed motion may decrease efficiency of MIMO systems. However, as in Fig. 3 — 6 for the subcases of transmitting shorter packets, the polylines for 2×2 MIMO systems in Fig. 7 are distinctly above the polylines for 3×3 MIMO systems, and the latter are above the polylines for 4×4 MIMO systems. As the motion speeds redoubles, the BER performance of 4×4 MIMO systems at the highest BENDR successively worsens approximately by 50 %. At lower BENDRs, the performance, although worsening, is far less "sensitive" to Doppler effects. Thus, the BER does not even double at the zero BENDR in 4×4 MIMO.
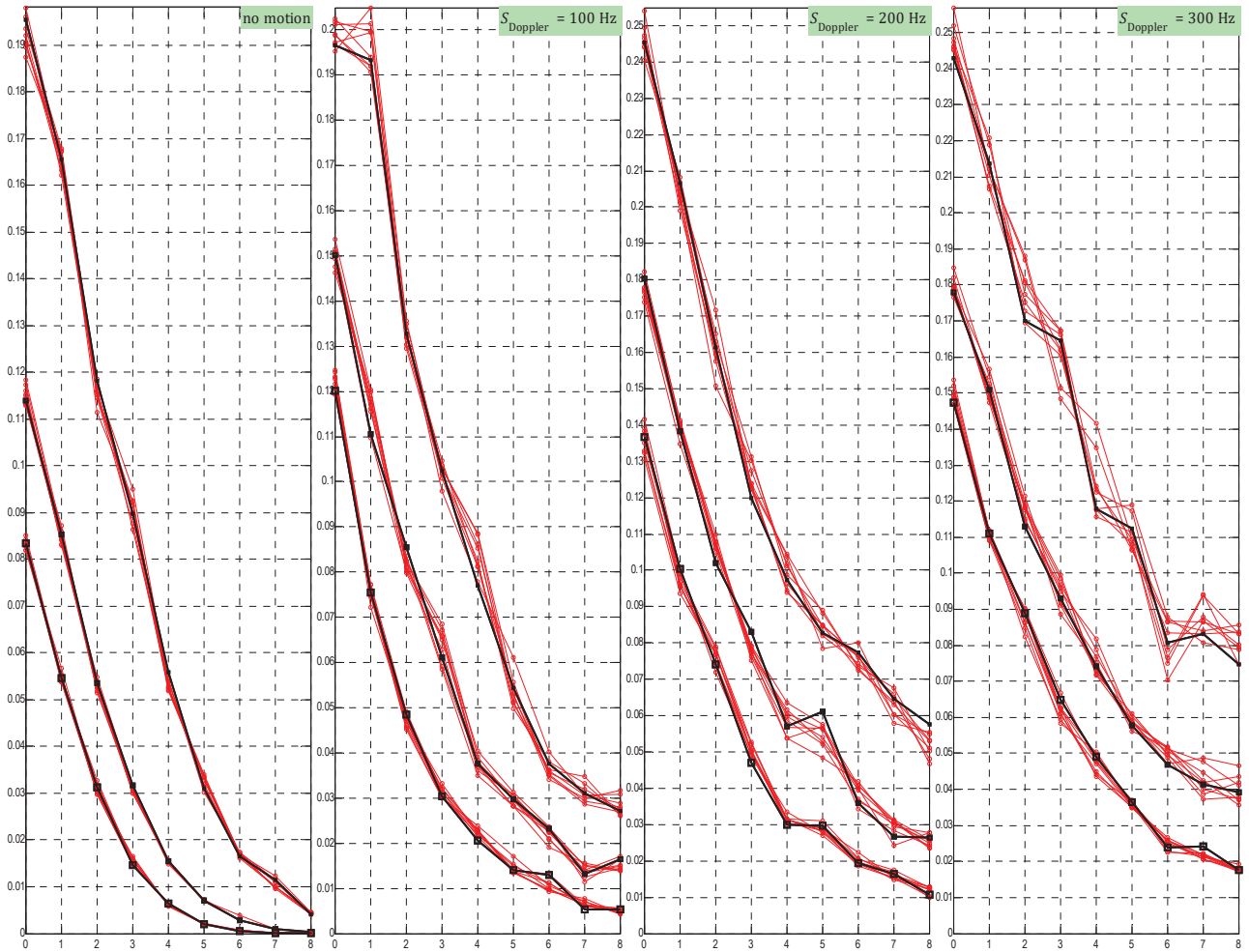
Fig. 7. The averaged BER performance versus BENDR

It is quite clear that the BER performance will further deteriorate as the motion speed continues increasing. Nevertheless, Doppler shifts greater than 300 Hz will fall out of modeling the scenario of DLoSPTR as distances corresponding to DLoSPTR are passed very fast then. Such cases are modeled by using Rayleigh fading distribution, where packets are transmitted through flat-fading Rayleigh channels [17].

5. Discussion

Surely, selection of OPSs is crucial to maintain an appropriate MIMO link data rate. In addition to this, too long packet transmissions by short OPSs (with respect to the packet length), like in the subcases of (5) — (9), (4), $\{F = 2304, P = 16\}$, $\{F = 2304, P = 32\}$, (15) — (17), (13), (14), (12), and (10), are prone to errors. This especially concerns 2×2 MIMO systems, where CSE by short OPSs appears to be ineffective or weakly effective.

A special attention should be paid to smoothness of a BER performance polyline. It is well seen in Fig. 3 —

6 that the smoothness starts getting shattered as the motion speed increases by transmitting longer packets with relatively short OPSs. Besides, the near-exponential-type decreasing of the polylines is violated also. The averaged BER performance in Fig. 7 confirms this as well. Thus, the near-exponential-type decreasing is almost not violated by no motion, whereas further speed increments destroy it for 2×2 MIMO systems. However, herein the near-exponential-type decreasing is less affected for 3×3 MIMO systems. The polylines for 4×4 MIMO systems, whose transmissions are effective, are not expected to be affected much.

Fig. 3 — 7 also show that, in the case of using orthogonal codes by PUBFs [12] instead of Walsh Hadamard-ordered functions, the CSE is not significantly improved. Bunches of polylines by PUBFs and Walsh Hadamard-ordered functions are more dispersed for MIMO systems with a lesser number of antennas. Obviously, the worst dispersion is for 2×2 MIMO systems. Surely, a more appropriate orthogonal set might be selected for such systems if its respective

BER polyline was always (or in most of the studied subcases) below the others. However, the latter is not confirmed by the simulation results.

6. Conclusion

Based on the simulation results, it is ascertained that the estimated BER performance of 2×2 to 4×4 MIMO systems with CSE by the OPSA is unfavorably influenced by Doppler effects in DLoSPTR modeled by the Rician fading distribution. In general, to maintain an appropriate MIMO link data rate, the packet length should be shortened as the motion speed increases. Increasing the number of antennas additionally mitigates Doppler effects. So, 4×4 MIMO system transmissions are indeed efficient. It is noteworthy that the shortest possible packet transmissions are not affected by Doppler effects if three or four antennas are used.

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Романюк В. В.

Вплив ефектів Доплера на системи MIMO від 2×2 до 4×4 з траєкторією радіохвиль при розповсюдженні у межах прямої видимості за розподілом завмирання Райса

Проблематика. Для збільшення пропускної здатності радіоканалу при використанні декількох антен на передавальному та приймальному кінцях, мережі бездротового зв'язку використовують техніку MIMO. Якість бездротового зв'язку MIMO може погіршуватися, коли передавач або приймач перебувають у русі, або вони обидва перебувають у русі. Для підтримки високоякісного зв'язку MIMO оперує, зокрема, інформацією про стан каналу за допомогою ортогональних пілотуючих послідовностей.

Мета дослідження. Мета полягає у тому, щоб оцінити продуктивність за рівнем помилкових бітів систем MIMO

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2×2, 3×3 і 4×4 з ортогональними пілотуючими послідовностями для деякого діапазону доплерівських зсувів за розподілом завмирання Райса, що моделює траєкторію радіохвиль при розповсюдженні у межах прямої видимості. Таке оцінювання має дати відповідь на питання про ефективність MIMO, з'ясовуючи те, чи збільшення кількості антен пом'якшує ефект Доплера у системах MIMO від 2×2 до 4×4 з траєкторією радіохвиль при розповсюдженні у межах прямої видимості.

Методика реалізації. Для досягнення мети проводиться симуляція систем MIMO від 2×2 до 4×4 з оцінюванням стану каналів. Симуляція та її конфігурування відбуваються за допомогою функцій MATLAB® R2019a Communications System Toolbox™. Розглядається 35 підвипадків довжини фрейму та кількості пілотних символів у фреймі.

Результати дослідження. Тип продуктивності за рівнем помилкових бітів, близький до експоненціального спадання, є майже непорушним за відсутності руху, тоді як подальші збільшення швидкості його руйнують для систем 2×2-MIMO. Виявлено, що передавання задовгих пакетів за коротких ортогональних пілотуючих послідовностей (відносно довжини пакета) піддане помилкам. Особливо це стосується систем 2×2-MIMO, де оцінювання стану каналів за коротких ортогональних пілотуючих послідовностей виглядає неефективним або слабкоефективним.

Висновки. У загальному, для того, щоб підтримувати прийнятний рівень передачі даних у MIMO-каналі, зі збільшенням швидкості руху довжина пакета має скорочуватись. Збільшення кількості антен додатково пом'якшує ефекти Доплера. Таким чином, передавання у системах 4×4-MIMO є дійсно ефективним. Ефекти Доплера не впливають на передавання якнайкоротших пакетів, якщо використовуються три або чотири антени.

Ключові слова: система бездротового зв'язку; MIMO; розподіл Райса; оцінювання стану каналів; ортогональні пілотуючі послідовності; ефект Доплера.

Романюк В. В.

Влияние эффектов Доплера на системы MIMO от 2×2 до 4×4 с траекторией радиоволн при распространении в пределах прямой видимости при распределении Райса

Проблематика. Для увеличения пропускной способности радиоканала при использовании нескольких антенн на передающем и приёмном концах, сети беспроводной связи используют технику MIMO. Качество беспроводной связи MIMO может ухудшаться, когда передатчик или приёмник находятся в движении, или они оба находятся в движении. Для поддержки высококачественной связи MIMO оперирует, в частности, информацией о состоянии канала с помощью ортогональных пилотирующих последовательностей.

Цель исследования. Цель состоит в том, чтобы оценить производительность по уровню ошибочных битов систем MIMO 2×2, 3×3 и 4×4 с ортогональными пилотирующими последовательностями для некоторого диапазона доплеровских сдвигов при распределении замирания Райса, которое моделирует траекторию радиоволн при распространении в пределах прямой видимости. Такое оценивание должно дать ответ на вопрос об эффективности MIMO, выясняя то, смягчает ли эффект Доплера увеличение количества антенн в системах MIMO от 2×2 до 4×4 с траекторией радиоволн при распространении в пределах прямой видимости.

Методика реализации. Для достижения цели проводится симуляция систем MIMO от 2×2 до 4×4 с оцениванием состояния каналов. Симуляцию и её конфигурирование производят при помощи функций MATLAB® R2019a Communications System Toolbox™. Рассматривается 35 подслучаев длины фрейма и количества пилотных символов во фрейме.

Результаты исследования. Тип производительности по уровню ошибочных битов, близкий к экспоненциальному убыванию, почти незыблем при отсутствии движения, тогда как дальнейшие увеличения скорости его разрушают для систем 2×2-MIMO. Выявлено, что передача длинных пакетов при коротких ортогональных пилотирующих последовательностях (относительно длины пакета) подвержена ошибкам. Особенно это касается систем 2×2-MIMO, где оценивание состояния каналов при коротких ортогональных пилотирующих последовательностях выглядит неэффективным или слабоэффективным.

Выводы. В общем, для того, чтобы поддерживать приемлемый уровень передачи данных в MIMO-канале, с увеличением скорости движения длина пакета должна сокращаться. Увеличение количества антенн дополнительно смягчает эффекты Доплера. Таким образом, передача в системах 4×4-MIMO действительно эффективна. Эффекты Доплера не влияют на передачу наиболее коротких пакетов, если используются три или четыре антенны.

Ключевые слова: система беспроводной связи; MIMO; распределение Райса; оценивание состояния каналов; ортогональные пилотирующие последовательности; эффект Доплера.