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# DOPPLER EFFECT IN 2×2 TO 4×4 MIMO SYSTEMS OF WIRELESS COMMUNICATION WITH ORTHOGONAL PILOT CHANNEL ESTIMATION

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## ABSTRACT

The Doppler effect in 2×2, 3×3, 4×4 MIMO wireless communication systems with channel estimation is studied. The orthogonal pilot signal approach is used for the channel estimation, where the Hadamard sequences are used for piloting, along with the eight alternative orthogonal sets similar to the Walsh set. MIMO transmissions are simulated for 10 cases of the frame length and pilot symbols per frame by no Doppler shift to 1100 Hz Doppler shift with a step of 100 Hz. Based on the simulation, it is ascertained that MIMO transmissions of shorter frames are less sensitive to the Doppler effect. Despite increasing the number of antennas does not mitigate the Doppler effect, and the bit-error rate performance of 4×4 MIMO systems worsens faster than that of 2×2 MIMO systems, it is better to use the maximum number of antennas. The Doppler effect does badly worsen the performance at highway and express train speeds (100 km/hr, and faster), leaving only possibility to further shorten transmissions. This, however, decreases the data rate, but the respective accuracy-versus-data-rate tradeoff must be acceptable.

Key words:

wireless communication, MIMO, Doppler effect, transmit-receive antenna pairs, bit-error rate.

**Research article**

## INTRODUCTION

As of 2020, the 5G wireless communication technology is still being embedded, where the MIMO technique is extensively used for multiplying the capacity of a radio link by using multiple antennas at the transmitter and receiver ends [1]. Where possible, massive MIMO systems are being implemented, but MIMO systems with just a few transmit-receive antenna pairs are believed to be still used at least for a decade.

To sustain high quality of links under combined effects of scattering, fading, and power decay with distance, MIMO operates on channel state information (CSI) [1, 3, 10]. The CSI is extracted from the received signal by using orthogonal pilot signals prepended to every packet [4]. If the CSI is based only on the received data, without any known transmitted sequence (which is called a blind approach), the tradeoff is the accuracy versus the overhead. Thus, the orthogonal pilot signal approach (OPSA) has a higher overhead, but it achieves a better channel estimation accuracy than the blind approach [15].

It is well known that the quality of wireless communication may worsen when either the transmitter or receiver end is in motion (or they both are). This occurs due to the Doppler effect [5, 9]. Obviously, influence of Doppler shifts on the MIMO performance at human-walking speeds is negligible. At vehicular speeds, however, the influence is experienced to be significant even by using CSI with OPSA. In particular, the data rate may dramatically decrease as the vehicle starts accelerating and keeps moving further at least at urban speeds, let alone highway speeds [9, 12].

## MOTIVATION AND GOAL

An end-to-end MIMO system is successfully simulated by using a random data generator, modulator [12], the orthogonal space-time block coding (OSTBC) technique [2, 11], fading channel models with additive white Gaussian noise [5], an OSTBC combiner [2], and a demodulator [3, 10]. These blocks are connected successively. The CSI with OPSA is commonly realized by orthogonal codes taken from the Hadamard matrix [12], where the first orthogonal sequence of pilot symbols is the sequence of ones. This sequence is the Walsh function of the zeroth order, which is a function-constant [13]. In particular, Walsh functions are generated from the Hadamard matrix [14], and can be used as well for other transmit antennas. Another possibility is to use alternative orthogonal sets similar to the Walsh set [6].

Whereas MIMO systems ensure high data rates and power efficiency, an open question is how indeed the Doppler effect influences the MIMO system with a few transmit-receive antenna pairs. Therefore, the goal is to estimate the bit-error rate (BER) performance of 2×2, 3×3, and 4×4 MIMO systems using CSI with OPSA for a wide range of Doppler shifts. For this, along with Walsh codes, alternative orthogonal sets in the OPSA are to be tried as well [6, 7], and various relationships of the frame length and pilot symbols per frame will be considered. The estimated BER performance is believed to answer the question by ascertaining whether increasing the number of antennas mitigates the Doppler effect. If the Doppler effect does badly worsen the BER performance, the respective breaking points or ranges should be described. Eventually, a possibility of using CSI with OPSA by more appropriate orthogonal sets is to be studied as well.

## SET-UP AND PARAMETERS OF THE SIMULATION

The set-up and simulation are based on MATLAB® R2019a Communications System Toolbox™ functions covering end-to-end MIMO systems which employ a few transmit and a few receive antennas. The random data are taken as pseudorandom integers drawn from the discrete uniform distribution on the interval from 0 to $M-1$, where $M$ is the number of transmit-receive antenna pairs. For using 2 to 4 transmit antennas, the signal is modulated by applying the quaternary phase shift keying (QPSK) method. The modulated signal is then encoded by using the OSTBC technique. The input symbols are mapped block-wise, and the output codeword matrices are concatenated in the time domain. It is worth noting that the symbol rate of the code is 1 for a 2×2 MIMO system, and 3/4 for 3×3 and 4×4 MIMO systems.

The frame length denoted by $F$ is set at 36, 72, 144, 288 symbols. The number of pilot symbols per frame denoted by $P$ cannot exceed 25 % of the frame length, so it is set according to tab. 1, with respect to each frame length. In an $M$×$M$ MIMO system, the $M$ pilot sequences of $P$-positioned codes are taken as the first $M$ Walsh Hadamard-ordered functions from the basis of $P$ functions. Alternatively, the $M$ pilot sequences of $P$-positioned codes are taken as the last $M$ functions from each of the eight orthogonal bases of $P$ partially unsymmetrical binary functions [6, 8].

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

| *F* | **36** | **72** | **144** | **288** | **frame length** |
|---|---|---|---|---|---|
| *P* | 8 | 8 | 8 | 8 | number of pilot symbols per frame |
| | *P* | 16 | 16 | 16 | |
| | | *P* | 32 | 32 | |
| | | | *P* | 64 | |

The modulated and encoded data are transmitted through flat-fading Rayleigh channels [12], to which white Gaussian noise is added. Each frame is passed by a ratio of bit energy to noise power spectral density. The ratio denoted by $r_{\mathrm{Eb/No}}$ is measured in dB. The range of $r_{\mathrm{Eb/No}}$ is set from 0 dB to 8 dB with a step of 1 dB. Besides, 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 [1, 12]. The number of errors cannot exceed 10 % of the number of packets, so the maximum number of errors is set at 5000, whereas the maximum number of packets is set at 50000. This number is believed to be sufficient for obtaining statistically stable (i. e., reliable) results of the simulation.

At the receiving end, the signals from all of the receive antennas and the channel estimate signal are combined to extract the soft information of the symbols encoded by the OSTBC. The combining algorithm uses only the estimate for the first symbol period per codeword block. The output of the combiner is demodulated using the QPSK method. Finally, the BER is estimated and fitted to a curve.

## RESULTS OF THE SIMULATION

For each of those 10 cases in tab. 1, the BER is plotted versus $r_{\mathrm{Eb/No}}$ with squared points for Hadamard sequences, and with circled points for the other orthogonal sequences from each of the eight above-mentioned orthogonal bases. The BER performance by no Doppler shift is shown in fig. 1. The polylines for 2×2 MIMO systems are above the polylines for 3×3 MIMO, and the latter are above the polylines for 4×4 MIMO. This order remains the same for the polylines of the BER by 100 Hz Doppler shift (fig. 2). The 200 Hz Doppler shift (fig. 3) and 300 Hz Doppler shift (fig. 4) also seem to have no significant influence on the BER performance.

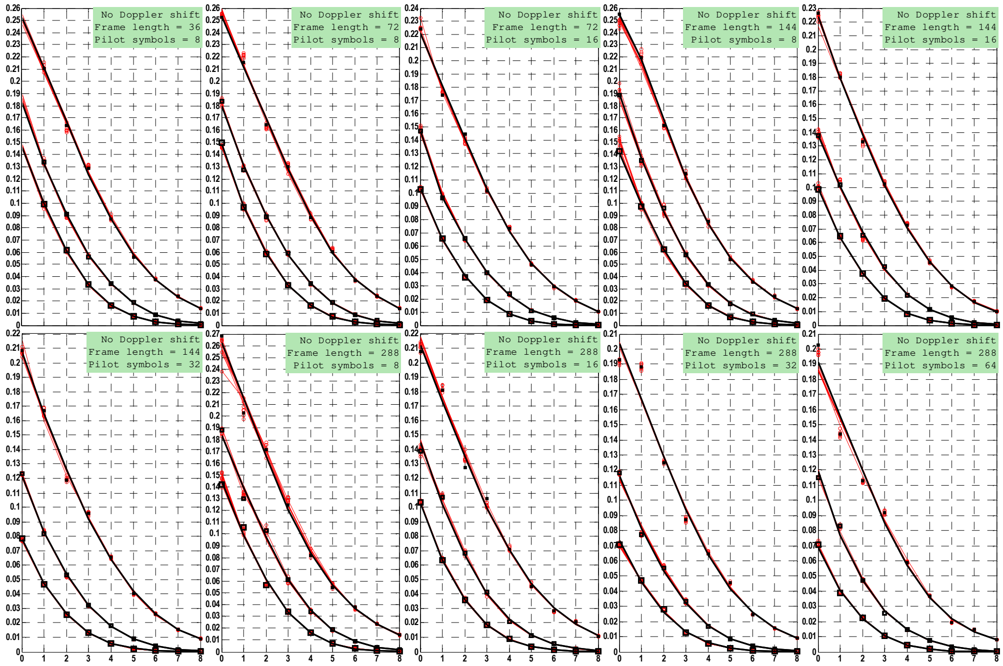


Fig. 1. The BER performance by no Doppler shift

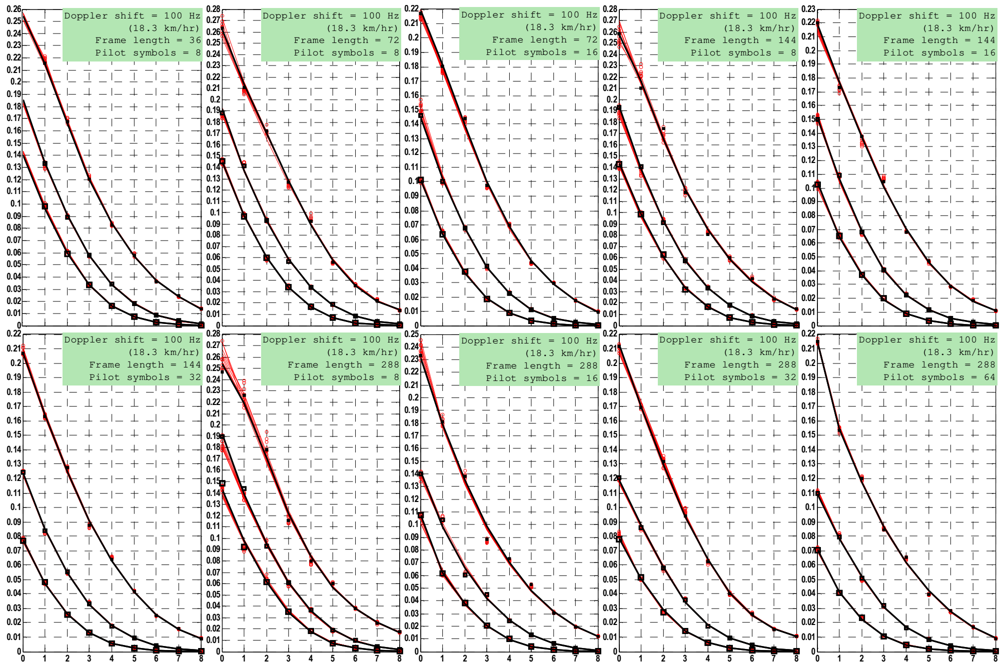


Fig. 2. The BER performance by 100 Hz Doppler shift

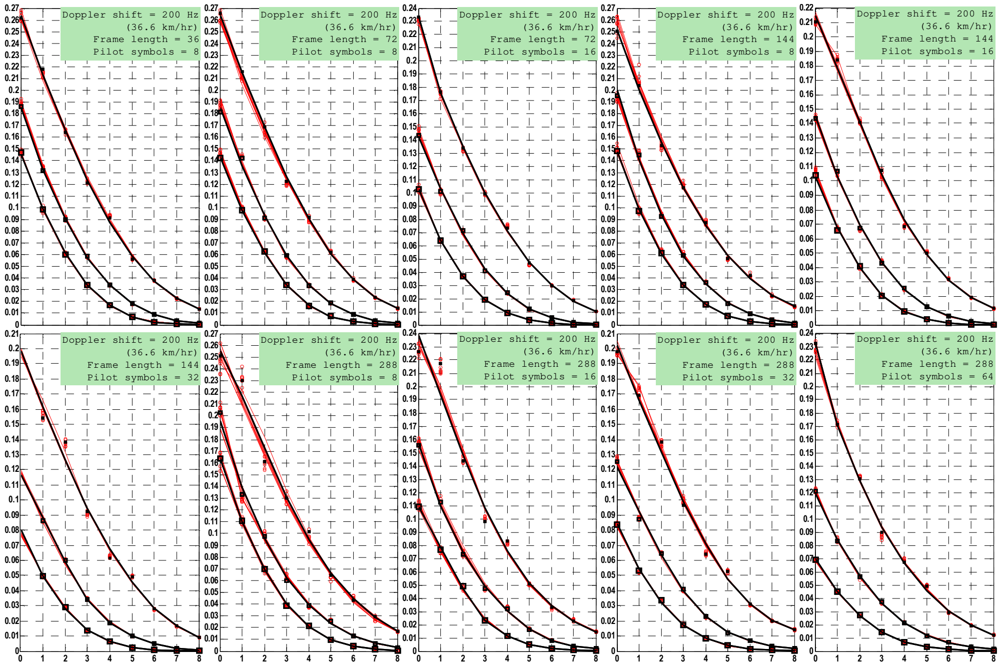


Fig. 3. The BER performance by 200 Hz Doppler shift

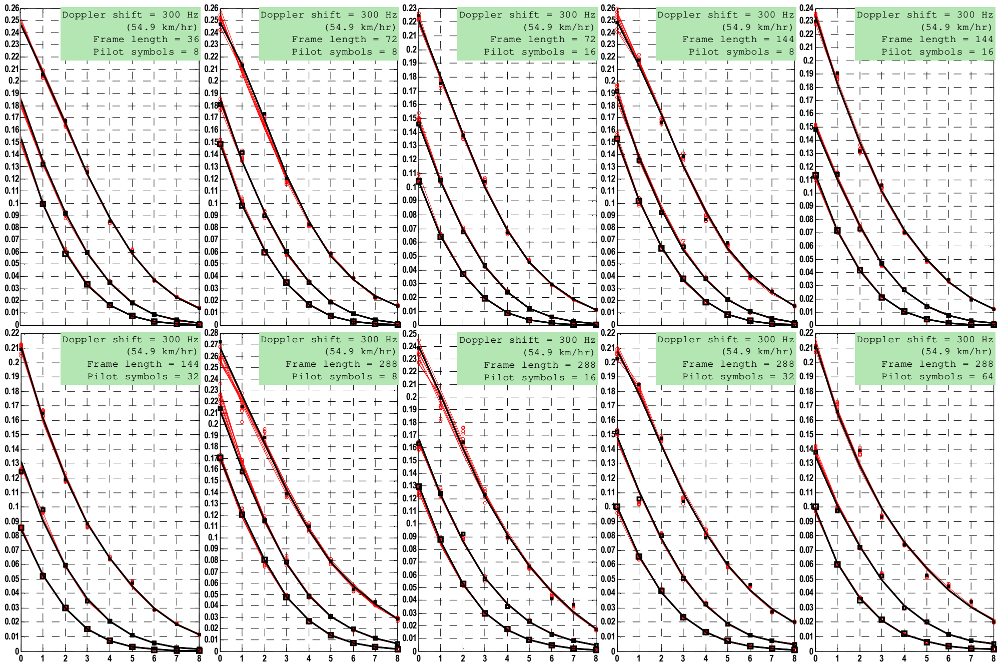


Fig. 4. The BER performance by 300 Hz Doppler shift

However, if to study the polylines in detail, the BER worsening is noticeable for the four following cases of the frame length and pilot symbols per frame:

$$\{F=288, P=8\},\ \{F=288, P=16\},\ \{F=288, P=32\},\ \{F=288, P=64\}. \quad (1)$$

Thus, even at urban speeds close to 60 km/hr, the long-framed 2×2 to 4×4 MIMO transmissions become slightly prone to the Doppler effect. Besides, the BER performance by

$$\{F=144, P=32\} \quad (2)$$

at such speeds for 3×3 and 4×4 MIMO systems (see fig. 3 and fig. 4) seems to be better than that by

$$\{F=288, P=64\}, \quad (3)$$

although the BER performance by (3) without motion (by no Doppler shift) is the best (see fig. 1).

Nevertheless, the BER here does not badly increase. It is worth to note that the speed ($\tilde{v}$) is estimated approximately by assuming that the carrier frequency is 5.9 GHz, whereas the general relationship is [9]

$$\tilde{v} = \frac{1.08 \cdot S_{\text{Doppler}}}{f_{\text{carrier}}} \quad (4)$$

for a Doppler shift $S_{\text{Doppler}}$ in Hz and a carrier frequency $f_{\text{carrier}}$ in GHz. So, lesser carrier frequencies correspond to faster motion. For instance, the speed by $f_{\text{carrier}} = 2.4$ GHz and 300 Hz Doppler shift is 135 km/hr, which is rather highway speed. The BER worsening for the cases of (1) at highway speeds cannot be reckoned noticeable.

At the Doppler shift of 400 Hz (fig. 5), it is especially noticeable that the BER of 4×4 MIMO at $r_{\text{Eb/No}} = 8$ dB for the cases of (1) becomes worse than that at $S_{\text{Doppler}} = 300$ Hz (fig. 4). The worsening builds up at $S_{\text{Doppler}} = 500$ Hz (fig. 6), which is quite obvious for 2×2 to 4×4 MIMO polylines for (1), and for

$$\{F=144, P=8\},\ \{F=144, P=16\} \quad (5)$$

as well. The Doppler shift of 600 Hz (fig. 7) already corresponds to a highway speed, at which polylines for (1) further distort. Their distortion in fig. 8 is such

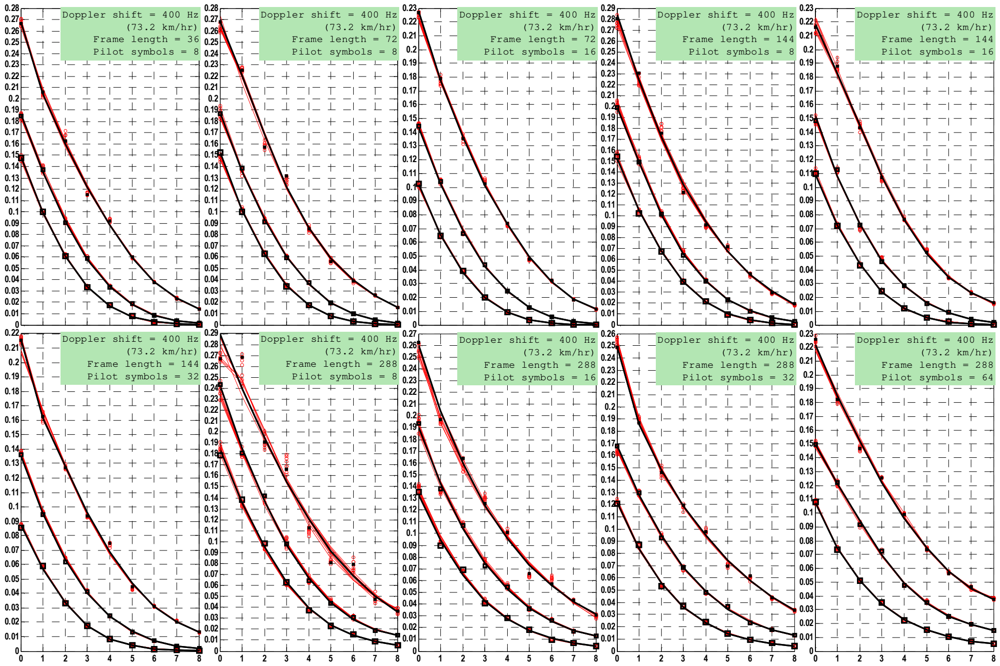


Fig. 5. The BER performance by 400 Hz Doppler shift

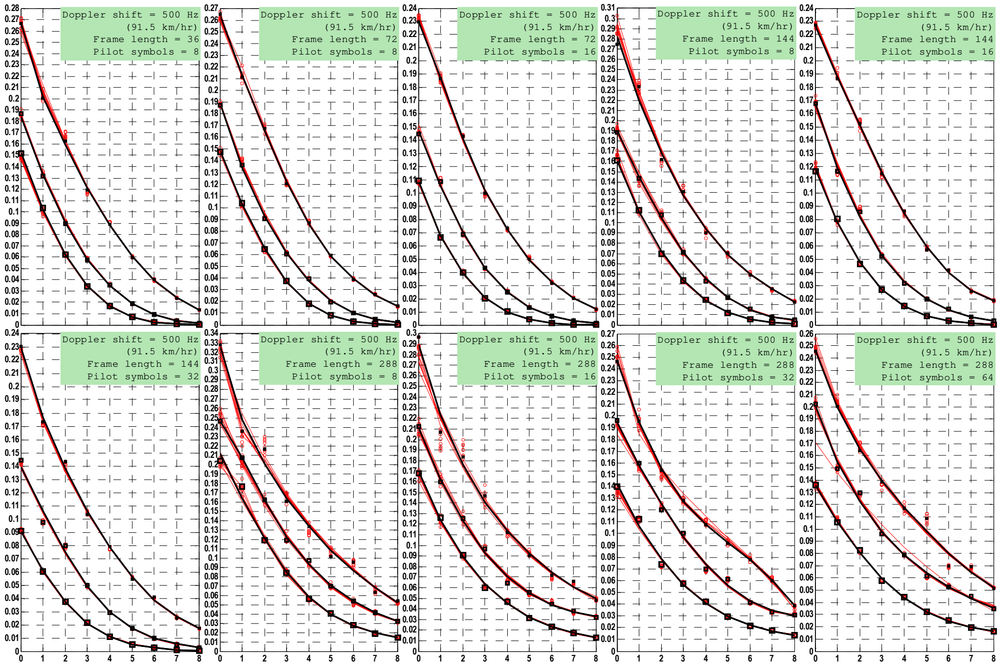


Fig. 6. The BER performance by 500 Hz Doppler shift

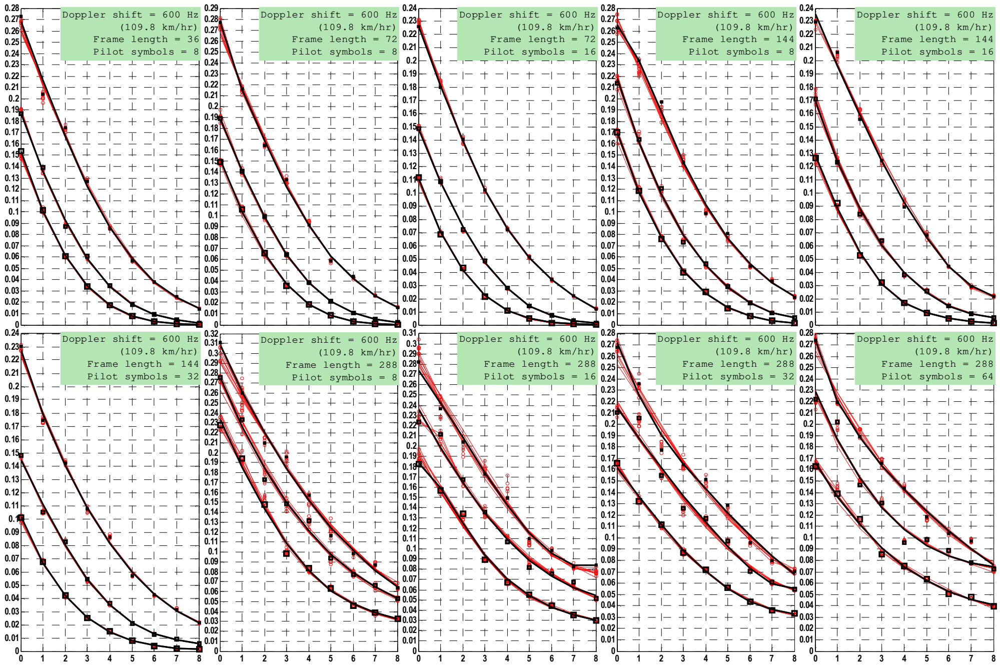


Fig. 7. The BER performance by 600 Hz Doppler shift

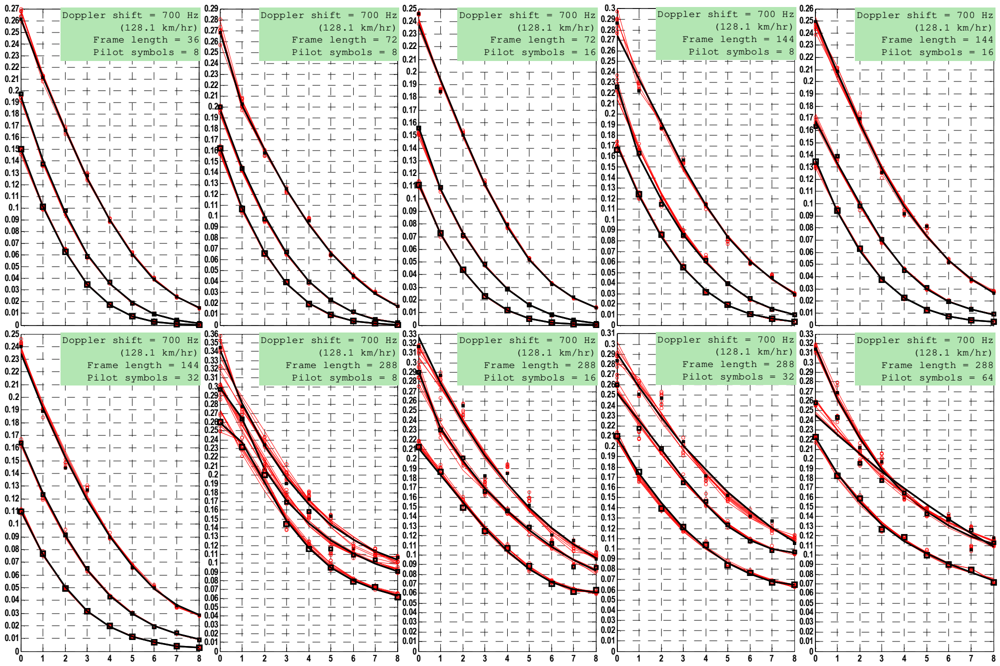


Fig. 8. The BER performance by 700 Hz Doppler shift

that the BER even at $r_{\text{Eb/No}} = 8$ dB for 4×4 MIMO is not less than 0.06, whereas the BER in the remaining six cases (see tab. 1) for 4×4 MIMO is still close to 0 at $r_{\text{Eb/No}} = 8$ dB.

It is obvious that, as the Doppler shift increases from 300 to 700 Hz (the speed increases from urban to highway), the BER performance by (2), i. e. by the medium-framed 2×2 to 4×4 MIMO transmissions, worsens significantly. Indeed, compared to the case without motion (by no Doppler shift), the BER at $r_{\text{Eb/No}} = 8$ dB for 2×2 MIMO has increased from 0.01 to 0.03, although the BER at $r_{\text{Eb/No}} = 0$ dB for 2×2 MIMO has increased from 0.21 to 0.24 (just about 14 %). The other medium-framed MIMO transmissions by (5) have "suffered" also, especially 3×3 and 4×4 MIMO at the Doppler shift of 600 Hz (fig. 7), where the motion speed exceeds 100 km/hr.

It is worth noting that short-framed 2×2 to 4×4 MIMO transmissions by

$$\{F = 32, P = 8\} \tag{6}$$

do not "feel" even the Doppler shift of 700 Hz (fig. 8). At the same time, their performance is still worse than that of MIMO transmissions by (2). However, the performance by (2) at this shift is almost equivalent to the performance by

$$\{F = 72, P = 16\}. \tag{7}$$

As the Doppler shift further increases (fig. 9 – 12), the polylines for long-framed 2×2 to 4×4 MIMO transmissions by (1) further exfoliate. The polylines for medium-framed 2×2 to 4×4 MIMO transmissions by (5) and (2) do not seem exfoliated, but their BER performance becomes visibly worse. The performance by

$$\{F = 72, P = 8\} \tag{8}$$

and (7) worsens also, but the respective polylines are not seen badly exfoliated even at $S_{\text{Doppler}} = 1100$ Hz (fig. 12), which corresponds to over 200 km/hr.

Amazingly enough, short-framed 3×3 and 4×4 MIMO transmissions by (6) are not influenced by the Doppler effect at highway and express train speeds. Indeed, the respective polylines in fig. 1 and fig. 12 are almost the same. However, the best BER performance at such speeds is produced by (7), where the BER at $r_{\text{Eb/No}} = 0$ dB for 4×4 MIMO is about 0.12, which is comparable to the averaged BER performance at urban speeds (see fig. 13 and its subplot for $S_{\text{Doppler}} = 300$ Hz).

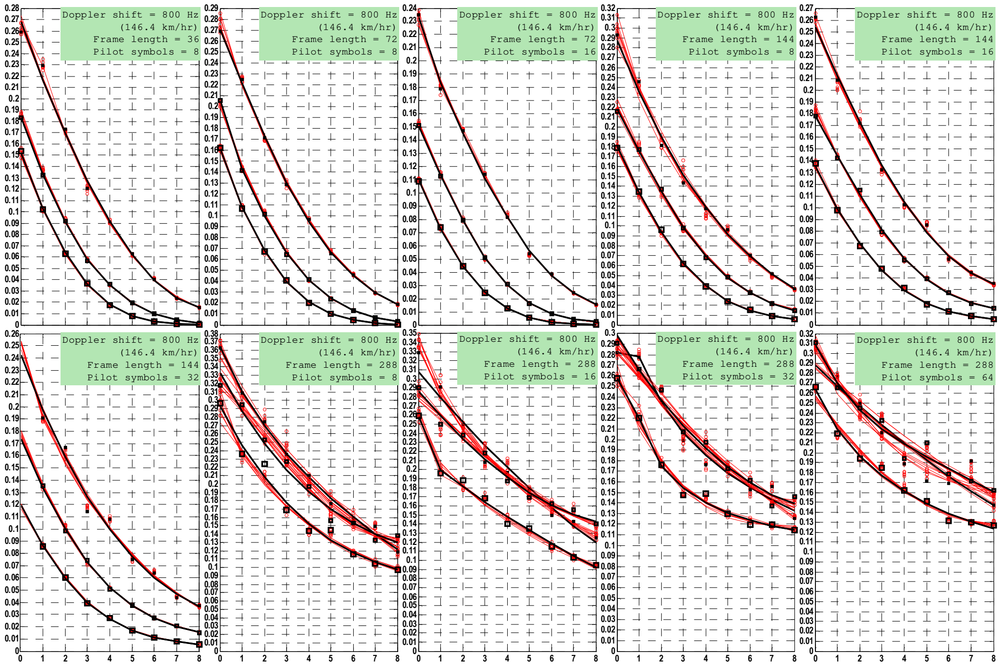


Fig. 9. The BER performance by 800 Hz Doppler shift

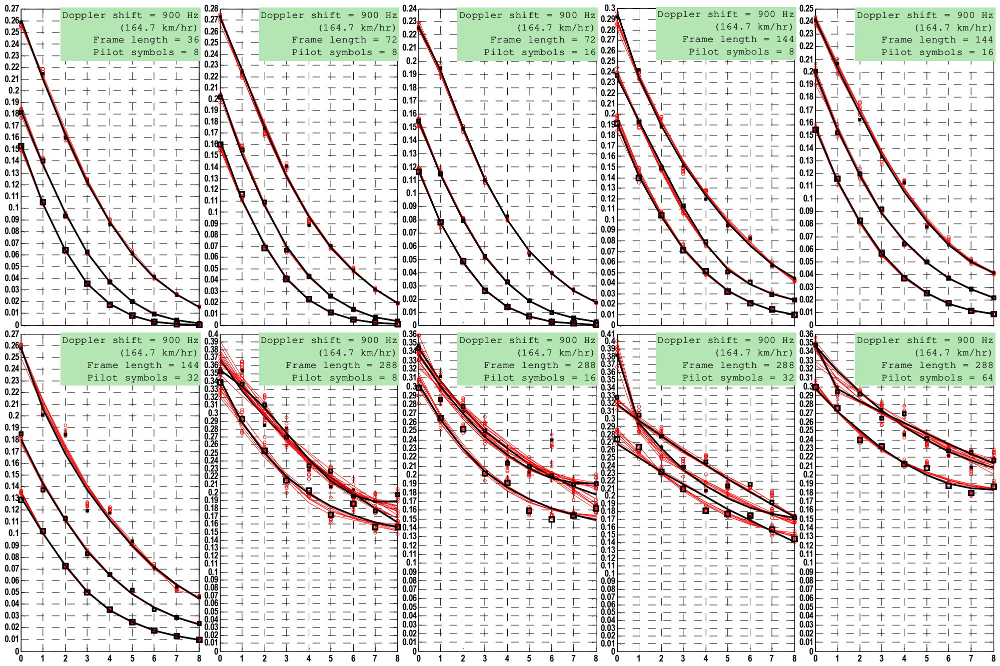


Fig. 10. The BER performance by 900 Hz Doppler shift

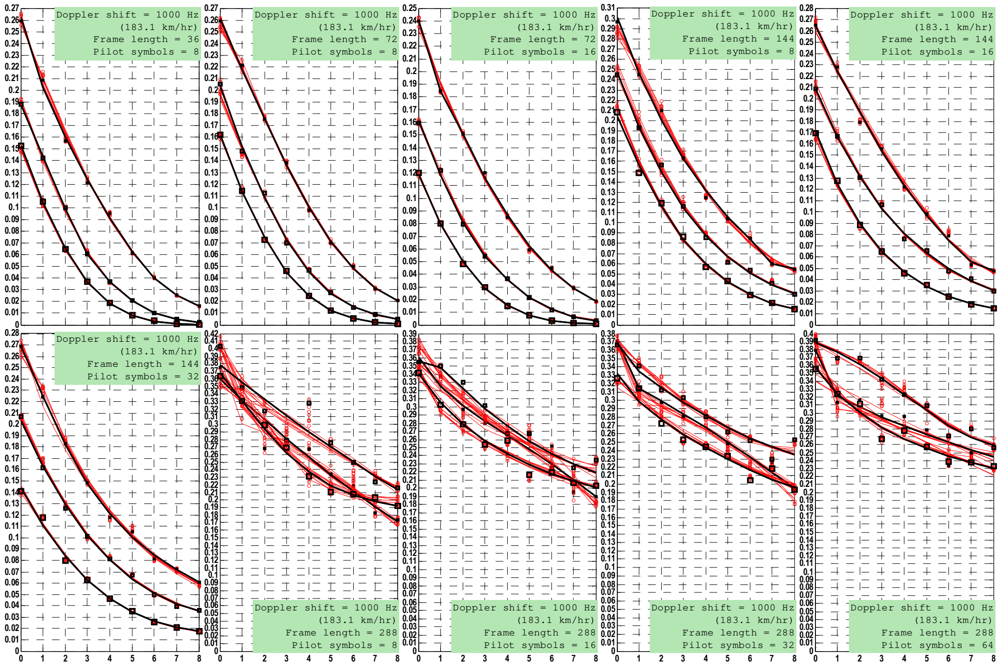


Fig. 11. The BER performance by 1000 Hz Doppler shift

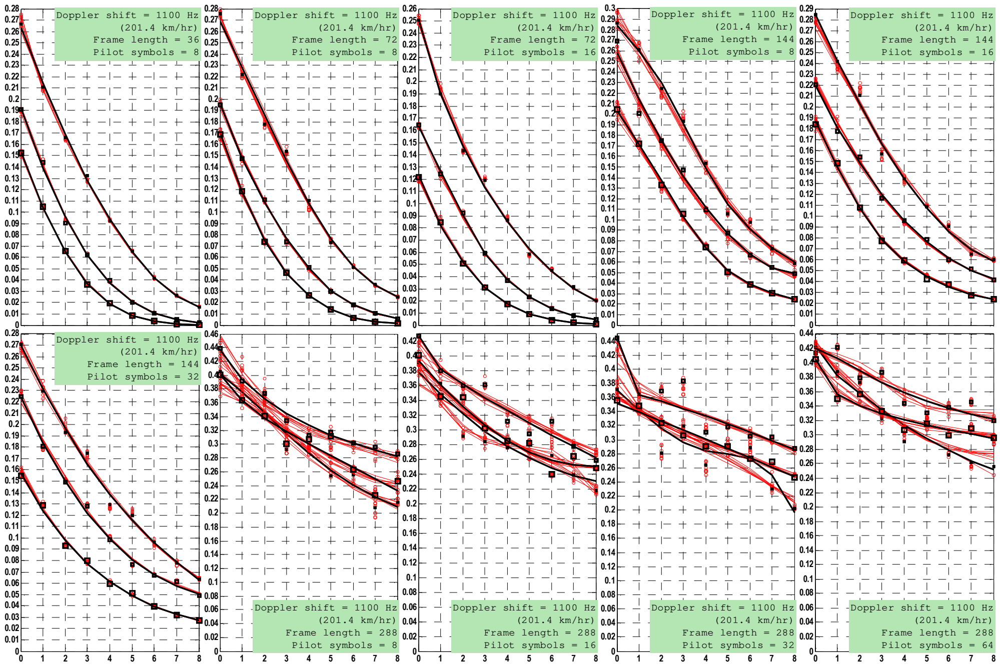


Fig. 12. The BER performance by 1100 Hz Doppler shift

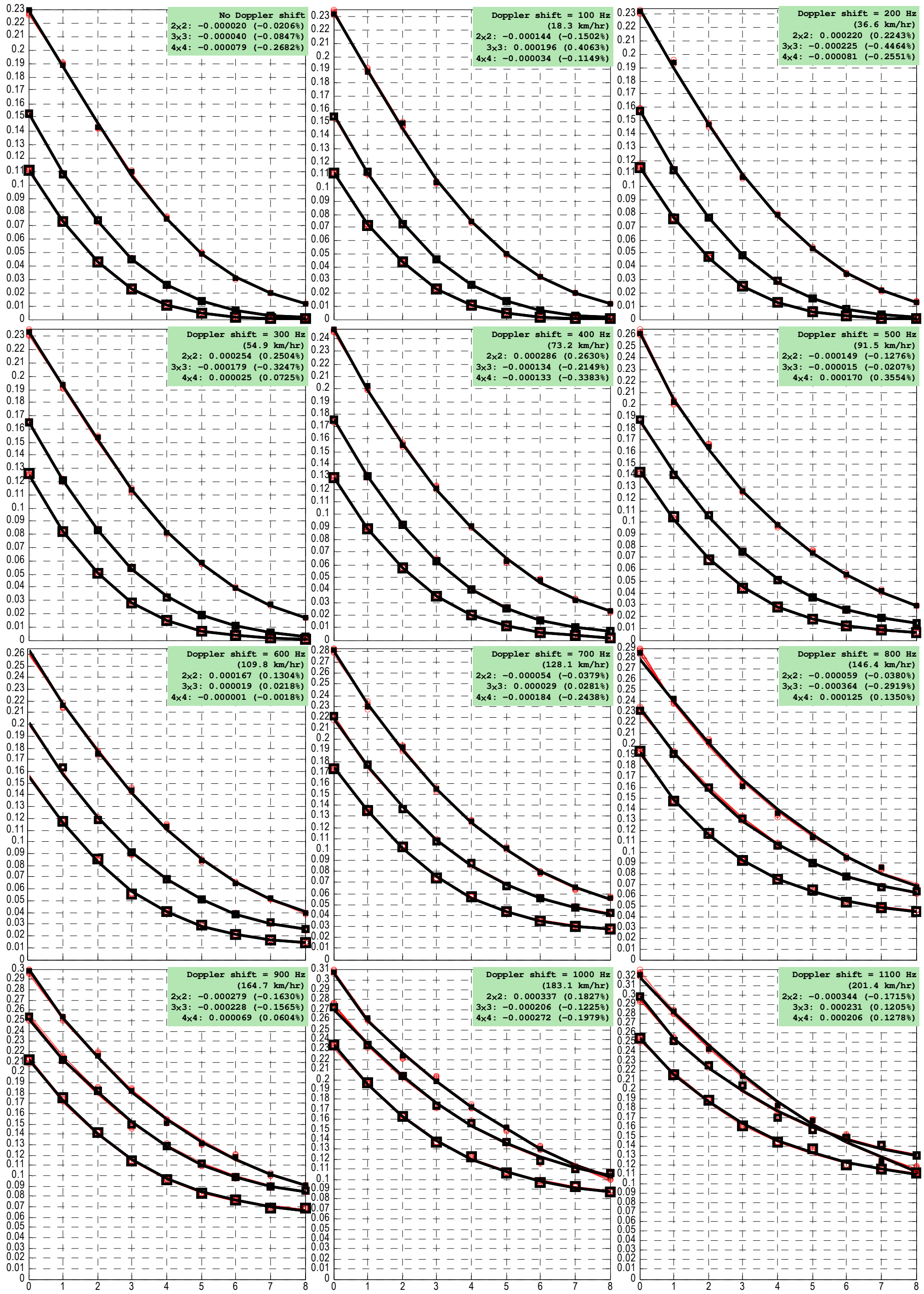


Fig. 13. The averaged BER performance by no Doppler shift to 1100 Hz Doppler shift

## DISCUSSION

The polylines in fig. 1 – 12 allow to see that the BER badly increases for MIMO transmissions of longer frames. In other words, the shorter the frame is, the less sensitive to the Doppler effect the MIMO system will be. Such sensitivity is clearly seen from the analysis of the respective polylines in fig. 1 – 12, which do have observable differences (their resemblance is delusive). Meanwhile, increasing the number of antennas does not mitigate the Doppler effect. Although the MIMO system with the greater number of transmit-receive antenna pairs has strictly better performance (up at urban and highway speeds), the BER of 4×4 MIMO systems worsens faster than that of 2×2 MIMO systems. For instance, at $r_{\mathrm{Eb/No}} = 0$ dB for 2×2 MIMO, the averaged BER increases from 0.23 (by no Doppler shift) to 0.3 (by 900 Hz Doppler shift), whereas it increases from 0.11 (by no Doppler shift) to 0.21 (by 900 Hz Doppler shift) for 4×4 MIMO (see fig. 13). In relative units, the performance decrement here is 30.4 % for 2×2 MIMO versus 90.9 % for 4×4 MIMO.

The 12 subplots in fig. 13 contain differences (in absolute units and percentage) between the averaged BER performance by the Hadamard sequences and partially unsymmetrical binary sequences [6, 8]. The differences are quite small (less than 0.5 %), and so they are insignificant. This implies that using CSI with OPSA by Hadamard sequences in 2×2 to 4×4 MIMO systems cannot be improved.

## CONCLUSIONS

The Doppler effect starts worsening the BER performance of 2×2 to 4×4 MIMO systems using CSI with OPSA at urban speeds close to 60 km/hr, and faster. This can be prevented by shortening the frame length (along with the respective length of pilot sequence). Despite increasing the number of antennas does not mitigate the Doppler effect, and the BER of 4×4 MIMO systems worsens faster than that of 2×2 MIMO systems, it is better to use the maximum number of antennas (by simultaneously shortening the frame length). At highway and express train speeds (100 km/hr and faster), it is impossible to use long-framed 2×2 to 4×4 MIMO transmissions, whichever the pilot sequence length is. The Doppler effect does badly worsen the BER performance at such speed ranges, leaving only possibility to further shorten transmissions (and thus decreasing the data rate). The respective accuracy-versus-data-rate tradeoff herein must be acceptable.

Using CSI with OPSA by orthogonal sequences similar to Hadamard sequences is possible but it does not improve the BER performance of MIMO systems against the Doppler effect. Nonetheless, the cases of the frame length and pilot symbols per frame and the range of Doppler shifts have been studied under presumption of the perfect orthogonality of pilot sequences. Surely, a de-orthogonalization in pilot sequences by using CSI with OPSA is not excluded, so this special case should be considered in a further research.

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# EFEKT DOPPLERA W SYSTEMACH KOMUNIKACJI BEZPRZEWODOWEJ OD 2×2 DO 4×4 MIMO Z OSZACOWANIEM KANAŁU PRZEZ PILOTA ORTOGONALNEGO

## STRESZCZENIE

W pracy przedstawiono badania efektu Dopplera w systemach komunikacji bezprzewodowej 2×2, 3×3, 4×4 MIMO z estymacją kanału. W procesie szacowania kanału zastosowano podejście sygnału pilotującego w wykorzystaniem sekwencji Hadamarda, wraz z ośmioma alternatywnymi zestawami baz ortogonalnych, podobnymi do zestawu Walsha. Transmisje MIMO zostały zasymulowane dla 10 przypadków, różniących się długością ramki i symboli pilotujących oraz częstotliwością Dopplera, której zakres zmieniał się od 0 do 1100 Hz z krokiem 100 Hz. Na podstawie badań symulacyjnych wykazano, że transmisje krótszych ramek MIMO są mniej wrażliwe na efekt Dopplera. Pomimo, że zwiększenie liczby anten nie zmniejsza efektu Dopplera, a wydajność współczynnika błędnych bitów w systemach 4×4 MIMO pogarsza się szybciej niż w systemach 2×2 MIMO, przeprowadzone badania wskazują na korzyści z zastosowania większej ilości anten. Efekt Dopplera znacznie pogarsza jakość transmisji przy prędkościach powyżej 100 km/h (ruch samochodów na autostradach lub pociągów ekspresowych), determinując potrzebę redukcji przesyłanych danych. To jednak zmniejsza szybkość transmisji danych, ale odpowiedni kompromis między dokładnością a szybkością przesyłania danych musi być akceptowalny.

Słowa kluczowe:

komunikacja bezprzewodowa, MIMO, efekt Dopplera, pary anten nadawczo-odbiorczych, współczynnik błędnych bitów.