jet INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2024, VOL. 70, NO. 4, PP. 797–803
Manuscript received August 19, 2024; revised October, 2024. doi: 10.24425/ijet.2024.149611

Evaluating the effectiveness of Doppler frequency shift determination using pilots in broadband transmission

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***Abstract*—In underwater communications, reciprocal motion between transmitter and receiver has a significant impact on reception quality. In orthogonal broadband systems that provide high bit rates, this problem becomes more important, especially in the higher frequency range, where the absolute Doppler shift is the greatest. Due to the low propagation speed of acoustic wave underwater, a substantial difference exists between the Doppler shift for lower and upper frequencies of the utilized spectrum. Consequently, a frequency-independent Doppler shift factor is employed. One of the most popular methods for determining the Doppler shift is the use of pilots. The problem of selecting the number and determining the frequency of pilots in such a way as to obtain the lowest possible error rate was identified. Real-world testing was conducted in a multipath propagation environment with relative speeds of up to 1.5 m/s. The effectiveness of Doppler shift determination was evaluated by analyzing the bit error rate. The results of the conducted tests indicate that, based on the achieved error rate, it is sufficient to employ 7 pilots positioned at low frequencies.**

***Keywords*—Underwater communication; multipath channels; Doppler shift; Doppler measurement; MFSK**

I. Introduction

THE water environment is characterized by very harsh propagation conditions, making it very difficult to implement wireless communications. This is due to the variability of its physical and chemical parameters in space and time, as well as its high attenuation. Currently, three key mediums of communication are considered in underwater transmission, namely acoustic, optical and electromagnetic waves. The last two are limited in use due to their very high attenuation or the need for a direct line of sight, which has led to their lack of popularity. Therefore the main topic of the article concerns acoustic wave.

Two physical phenomena are major problems to establishing and maintaining high-speed, low-error-rate underwater transmission, namely multipath propagation and the Doppler effect. The first is important in shallow water areas and those with intensive hydrotechnical structures, such as ports, canals, etc., and leads to multiplication in the receiver of the transmitted signal arriving via different paths, and this in turn is the cause of frequency-selective fading and intersymbol interference. The second phenomenon occurs when the receiver and transmitter move relative to each other, which manifests itself as a frequency shift. Very often, both phenomena occur simultaneously, which additionally leads to spreading of the signal in the frequency domain, i.e. Doppler spread. Incorrect frequency determination may completely prevent proper reception of the transmitted information. In broadband systems that provide high bit rates, this problem becomes more important, because the Doppler shift at the edges of the utilized spectrum differs significantly. To remedy this on the receiving side, the propagation conditions of the received signal must be known. Knowing these is possible by transmitting signals with known parameters, and then determining deviations from these parameters based on the received signal. Due to the low propagation speed of an acoustic wave in water, there is a significant difference between the Doppler shift for the lower and higher frequencies of the spectrum used. Therefore, instead of using the concept of Doppler shift, which is determined for a given carrier frequency, it is much more convenient to use the frequency-independent Doppler factor μ.

One of the most popular methods in the field of determining the Doppler factor is the transmission of so-called pilots, that is, sinusoidal signals with predefined frequencies. Their identification on the receiving side makes it possible, by comparing the received frequency with the transmitted one, to determine the Doppler factor. If, apart from the Doppler effect, also a multipath effect occurs, each of the signal paths may experience a different Doppler factor.

The problem of determining the Doppler shift is discussed in the literature. It concerns various communication systems, both underwater [1]–[4] and radio [5]–[8]. Article [1] presents an in-depth mathematical analysis that leads to a determination of what dependencies the Orthogonal Frequency-Division Multiplexing (OFDM) signal should satisfy in order for a given Doppler shift to be detected. The research was carried out by simulation only, and the Doppler phenomenon was simulated by resampling the signal. Determination of the Doppler shift is realized by means of carriers in the OFDM signal. The

This work was supported by the National Centre for Research and Development under Project DOB-SZAFIR/01/B/017/04/2021.

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article lacks quantitative comparisons and analysis of the effect of Doppler shift estimation on reception quality. The authors an article [2] propose a new method of Doppler shift compensation for underwater acoustic communication systems based on OFDM. To save bandwidth, they do not use an additional signal header (preamble) in each OFDM frame, as is the case in many conventional approaches and instead, the central subcarrier is reserved for pilot transmission and is used to detect the Doppler frequency. Two synchronization stages are used in the receiver. The advantage of using pilots in the proposed method is that the OFDM frame length is reduced and therefore the system throughput can be increased. The proposed method is able to track the rapid variation of Doppler frequency over time, which is a typical feature of an underwater channel. The study was conducted in a real underwater channel with a relative velocity of 3 m/s. The paper [3] considered horizontal, shallow water channels characterized by extremely unfavorable transmission properties due to strong multipath propagation and refraction phenomena. Due to the fact that the signal transmitted in the Underwater Acoustic Communication (UAC) suffers from time dispersion, which manifests itself in the selective fading of the signal spectrum, the author uses pilots to reduce the negative impact of this phenomenon on the information detection process. This paper presents the results of communication tests conducted during an inland-water experiment using a laboratory model of a UAC system implementing the OFDM technique. Based on the estimated transmission parameters, four configurations of OFDM modulation parameters were selected and connectivity tests were conducted for each of them using two error-corrected coding (ECC) techniques. In each case, the coding efficiency for which reliable data transmission is possible with a Bit Error Rate (BER) of less than 10^{-4} was determined. The paper [4] used pilots for channel estimation. Since the Underwater Acoustic (UWA) channel is both time and frequency varying, channel estimation becomes complicated. The authors proposed a pilot-based channel estimation technique and studied two equalizers to improve the error performance of an OFDM-based UWA system. Both equalizers use pilot subcarriers to estimate the UWA channel. Using computer simulations, they observed that the number of pilots should be one-fourth of the number of subcarriers to achieve acceptable reception quality. Moreover, if the energy of the pilots is increased without changing the overall symbol energy, the error rate will deteriorate. The authors of the article [5] use pilots but transmitted as pulses during transmission to determine Doppler. As a result of their study, they found that when Signal-to-Noise Ratio (SNR) is very low, data symbols' contribution to the carrier frequency estimation would be much less than pilot symbols. Only simulation studies were presented and the results concerned only the error of determining the Doppler shift, without assessing the impact of this estimation on reception quality. In [8], an analysis of the application of the orthogonal frequency division multiple access (OFDMA) method with pilot signals in cellular systems is presented. The main purpose of the study and simulation was to investigate the effect of the Doppler effect on orthogonality interference in critical but real-world situations. Articles [6] and [7] deal with the use of pilots in satellite systems. In [6], the effectiveness of Doppler correction based on Phase-Locked LoopS (PLL) and introduced additional pilots to the 8th order Phase Shift Keying (8PSK) signal based on simulation only was compared. A Low Earth Orbit (LEO) satellite link was considered. Doppler compensation is implemented by phase compensation only. The study shows that for SNR < 6 dB significantly better results are obtained for pilots. For higher SNR, the PLL loop is significantly better - it coincides with the theoretical BER curve. The effectiveness of the methods was compared by BER in reception. Unfortunately, due to analyzed satellite channels, in the described studies, the effect of multipath was not analyzed, which is crucial in underwater communication. Moreover, the Doppler effect was simulated in a very simplified way. In [7], an algorithm is proposed to accurately estimate the Doppler frequency of a LEO satellite in a downlink based on the joint use of an explicit pilot signal and an implicit pilot, which is a signal segment opportunistically available in a LEO downlink frame with a sequence of zero bits, sequence of one bits, or sequence of interleaved zero and one bits. Theoretical performance was derived, and simulation results show that the proposed algorithm achieves the Cramer-Rao lower bound (CRLB). Verifications were performed on signals from the Iridium mobile satellite communications system.

Accordingly, it was decided to evaluate the effect of the deployment of pilots and their number in broadband transmission on the efficiency of Doppler factor determination verified by the BER, which is the purpose of this research. The research carried out will add to the knowledge of the use of pilots, particularly their placement and number in broadband transmission to improve reception quality. In the available literature, the authors have not encountered studies that discuss the impact of the deployment and number of pilots on transmission quality under conditions of strong multipath and long channel memory time, expressed at least in terms of bit error rate. The results are presented on the basis of experiments conducted under real, very difficult, propagation conditions. Therefore, this element is considered as some novelty.

The paper has the following organization, the second chapter details the transmitted signals, encompassing various configurations of pilots and their utilization in estimating the Doppler factor. The third chapter focuses on the measurement setup, outlining the equipment used and the conditions under which the tests were conducted. Subsequently, the fourth chapter describes the results obtained at different movement speeds.

II. TRANSMITTED SIGNAL

The data transmission was conducted employing MFSK (Multiple Frequency Shift Keying) modulation, extensively detailed in [9]. Our prior research has established that this modulation is very resilient to multipath effect prevalent in our environment. For each bit two carrier frequencies are provided, however only one is utilized depending on the value of the particular bit. The carrier spacing, denoted as F_{db}, was set to

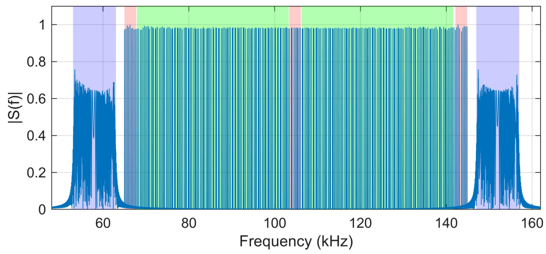

Fig. 1. Spectrum of one transmitted package, the blue area shows chirp signals, the green area shows MFSK signal, and the red area shows pilots band.

160 Hz, resulting in a signal bandwidth of 80 kHz, with the central frequency, f_c, set at 105 kHz. The signal duration was 50 ms and was modulated with randomly generated data. Such generated signal will be called the "MFSK symbol".

Pilots were positioned at the start, end, and in the middle of the MFSK signal's bandwidth to estimate the Doppler factor μ, which can be calculated as:

$$\mu = \frac{1}{N}\sum_{k=0}^{N}\frac{f_k'}{f_k}, \tag{1}$$

where f_k represents the frequency of the transmitted pilot k, f_k' is frequency of the received pilot k, and N is the number of pilots. This factor defines the ratio between the transmitted and received frequencies. Hence, the Doppler factor is indispensable in wideband signal transmissions. The pilots were spaced identically to the rest of the MFSK signal and positioned within the following bands:

- 65 – 67.72 kHz band,
- 103.4 – 106.12 kHz band,
- 142.12 – 144.84 kHz band.

However, these bands are applicable when utilizing 9 pilots, as the number of pilots decreases, the bands proportionally decreases.

Concurrently with data transmission, chirp signals were sent at frequencies 58 kHz and 152 kHz, each with a bandwidth of 10 kHz. Two chirp signals were transmitted on each frequency, one with increasing frequency (Up Chirp), and the other with decreasing frequency (Down Chirp). However, only Up Chirps located in higher frequencies were utilized in this scenario. They were necessary for symbol synchronization [10], [11] and impulse response measurement. Spectrum of the combined MFSK, pilots, and chirp components, which later will be called as a "transmitted package", are depicted in Fig. 1.

III. Doppler Factor Estimation Algorithm

To estimate the Doppler factor using the pilots from the selected band, the algorithm presented in Fig. 2 was developed. This algorithm requires the signal in the time domain, $s(t)$, containing one transmitted package, the frequencies of the pilots sent, and the designated band for Doppler factor estimation. Initially, the signal in the time domain, $s(t)$, is converted to the signal in the frequency domain, $|S(f)|$, using the FFT (Fast Fourier Transform). Prior to the conversion, the signal $s(t)$ is zero-padded to enhance the frequency resolution of $|S(f)|$.

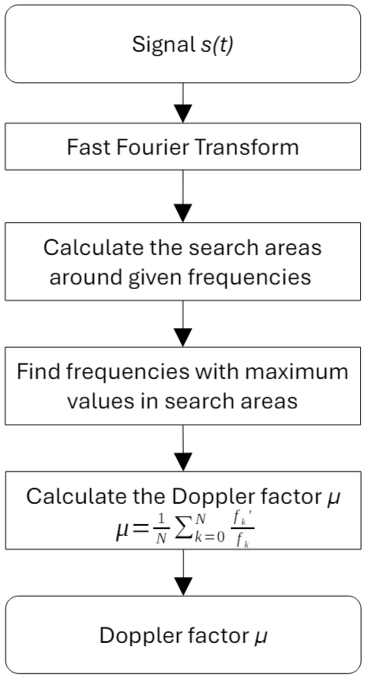

Fig. 2. Flow graph of the Doppler factor estimation algorithm

Subsequently, the estimation of the Doppler factor using pilots from the selected band begins. Knowing the frequencies of transmitted pilots, f_k, the search areas around them are indicated. In each of these areas the frequencies with maximum values of $|S(f)|$ are searched, marked as f_k'. Afterwards, according to the equation 1, the Doppler factor, μ, is determined. This process is repeated for each of the pilot bands utilized.

IV. Measurement Conditions

The signal was generated in a Matlab environment, then converted to analog signal using a NI USB-6366 digital-to-analog converter (DAC), amplified by an ETEC PA1001 power amplifier, and transmitted via the Reson TC4013 transducer. At the receiving end, four Reson TC4013 transducers were deployed. The received signal was amplified by an ETEC A1105A transducer amplifier, digitized by a NI USB-6366 analog-to-digital converter (ADC), and saved.

The measurements were conducted in the freshwater towing tank of the Faculty of Mechanical Engineering and Ship Technology at the Gdansk University of Technology, depicted in Fig. 3. This tank is characterized by a strong multipath effect, as proven in our previous publication [12]. As illustrated in the figure, the water block measured 4 m in width, 3 m in height, and 40 m in length. The transmitting transducer was concealed within the mast, which was affixed to the movable platform, as presented in Fig. 4. This transducer was placed in the middle of the tank's width at a depth of 1 m underwater. The mast shielded the transducer from water flow, and the entire assembly was reinforced with steel lashings to ensure stability and mitigate vibration during motion. The receiving

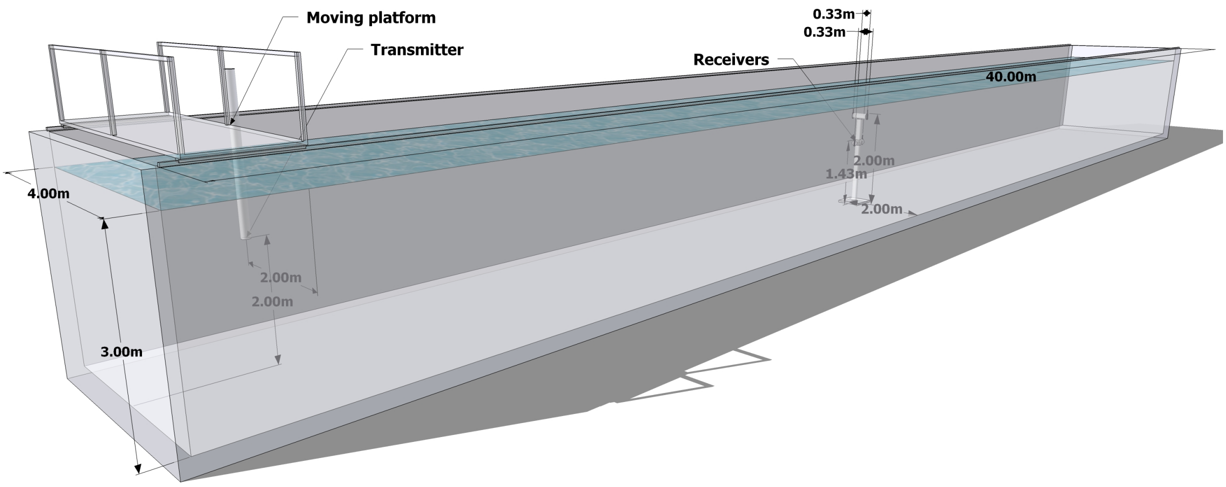

Fig. 3. Measurements setup in the towing tank with the transmitting and receiving transducers.

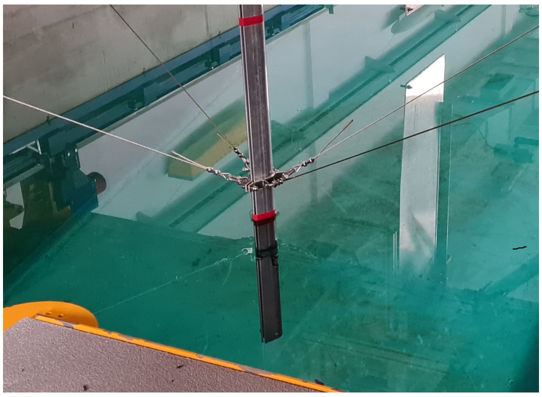

Fig. 4. Mast containing the transmitting transducer, reinforced with steel lashing

Fig. 5. Submerged mast with the receiving transducers

transducers were mounted on a mast anchored to the tank's bottom, in line with the transmitter, as depicted in Fig. 5. This arrangement situated two transducers at a depth of 2 m and two at 1.43 m underwater. The separation between the transducers at the same depth was 0.33 m.

During measurements, the transmitting transducer was set in motion to create the Doppler effect. The movable platform could achieve speeds of up to 2 m/s with a precision of 0.01 m/s, although tests were conducted at speeds of 0.5, 1, and 1.5 m/s. Measurements at each speed were repeated six times. For the analysis presented in this article, only data collected at distances of 3 to 10.5 meters between the transmitter and receiver were used to minimize power loss effect at greater distances and rapid changes in the angle between the transmitter path and the receiver at shorter distances. The theoretical value of the Doppler factor can be calculated as follows:

$$\mu = \frac{c + v_r}{c + v_s}, \quad (2)$$

where c denotes the speed of the acoustic wave underwater (measured with a Valeport SWIFT CTD plus probe to be 1476 m/s), v_r is the speed of the receiver (positive for approaching, negative for departing), and v_s indicates the speed of the source (positive for departing, negative for approaching). In the conducted experiment, only the transmitter was moving, so v_r equals 0. Since the transmitter was approaching the receiver, the speed values in the formula will be negative. The calculated values of the Doppler factor for the selected speeds are presented in Table I.

V. Results

In the current section are presented analyses which illustrate the relationship between the Doppler factor μ and the

TABLE I
THEORETICAL VALUES OF THE DOPPLER FACTOR μ FOR THE SELECTED SPEEDS

Speed of the transmitter [m/s]	Calculated value of the Doppler factor
1.5	1.00102
1	1.00068
0.5	1.00034

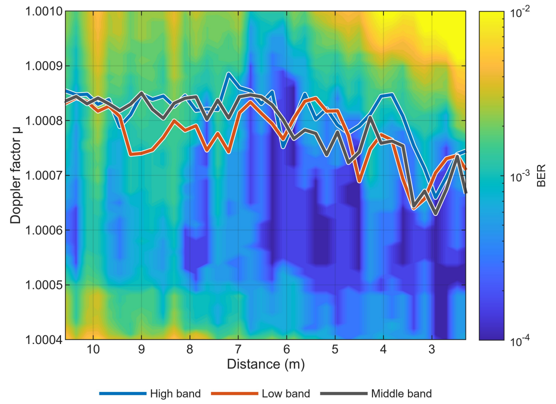

Fig. 6. The relationship between the Doppler factor μ and the distance between the transmitter and receiver for different bands of 7 pilots during the transmitter movement speed of 1.5 m/s.

distance. The data for these graphs contains collections of all measurements, synchronized according to distance. There were 6 runs of the transmitter. During each run, data was concurrently collected by 4 receiving transducers, which are treated as independent transmissions in these analyses as they were separated by couple of wavelengths. This approach resulted in each point being represented by the average of 24 Doppler factor values (calculated from 6 runs multiplied by 4 transducers). These graphs are overlaid onto heatmaps, showing the approximated BER through demodulation with utilization of each possible Doppler factor at each distance point. The BER values averaged over the analyzed range for the estimated, based on pilots signals, Doppler factor from the pilots are depicted in the bar plots.

Figure 6 shows the Doppler factor μ as a function of the distance received with the use of 7 pilots transmitted at different bands during the transmitter movement speed of 1.5 m/s. As the distance decreases, a slight decrease in the Doppler factor is observed. It can be explained by the multipath effect. The non-direct propagation paths experience lower Doppler shifts. Therefore, the estimated Doppler factor in the receiver is an averaged value of signals received from all paths. Although all lines shown in the graph exhibit similar values slightly above the area of the lowest BER values.

Figure 7 depicts the Doppler factor μ as a function of the distance received for different numbers of pilots placed in the middle band during the movement speed 1.5 m/s of the transmitter in the direction of the receiver. The presented graphs exhibit greater similarity to each other compared to Fig. 6 - the greater influence on the estimated Doppler factor has the pilots frequencies than the number of pilots. Additionally,

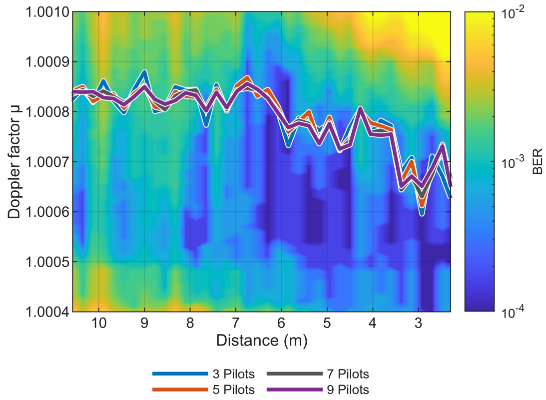

Fig. 7. The relationship between the Doppler factor μ and the distance between the transmitter and receiver for different numbers of pilots placed in the middle band during the transmitter movement speed of 1.5 m/s.

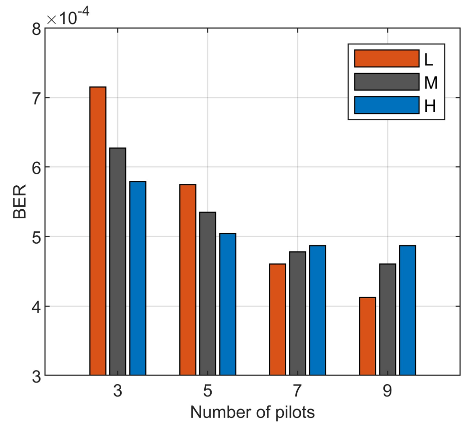

Fig. 8. Averaged BER for different configurations of pilots during the transmitter movement speed of 1.5 m/s.

it is apparent that with a greater number of pilots, the values fluctuate less. Notably, the line representing 3 pilots displays the greatest deviation from other lines.

Figure 8 presents obtained BER for different configurations of pilots during the transmitter movement speed of 1.5 m/s. The worst results were obtained using only 3 pilots placed in the low band. A significant decrease in BER is observed with an increase in the number of pilots up to 7. Additionally, for 3 and 5 pilots, the higher the bandwidth the lower BER values were achieved. Although this relation reverses with 7 and 9 pilots.

Figure 9 represents the Doppler factor μ as a function of distance for a single measurement using different number of pilots in the low band during the movement speed 1.5 m/s. The high number of errors, as in the case of 3 pilots placed in the low band (Fig. 8), can be attributed to the distances in which the Doppler estimation overshot its value to a degree of placing it outside the low BER area. Notably, in one symbol between the eighth and ninth meter, the Doppler factor estimated using only 3 pilots, fell within the yellow area (Fig. 9), indicating a significant number of errors, as demonstrated in Fig. 10. In all other MFSK symbols, the BER did not exceed 10^{-2}.

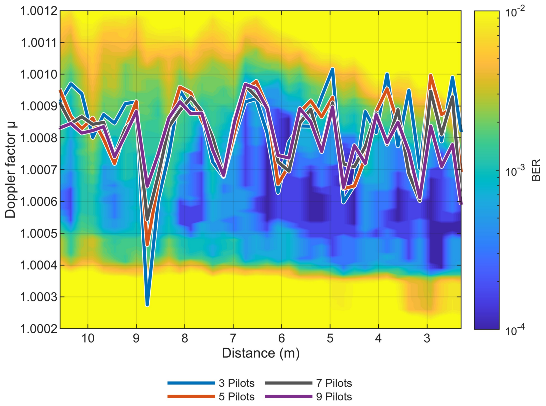

Fig. 9. The Doppler factor μ as a function of distance for a single measurement using different number of pilots in the low band during the movement speed 1.5 m/s.

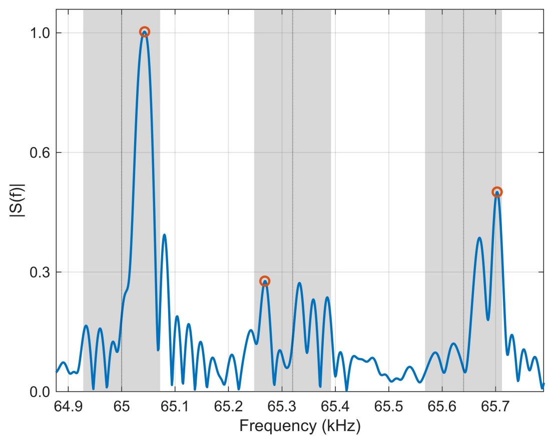

Fig. 11. Fragment of a spectrum with allocated pilots for the symbol with incorrect Doppler estimation.

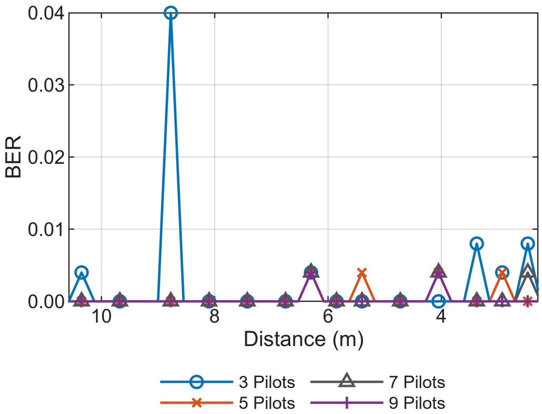

Fig. 10. BER as a function of distance for single measurement using different number of pilots during the transmitter movement speed of 1.5 m/s.

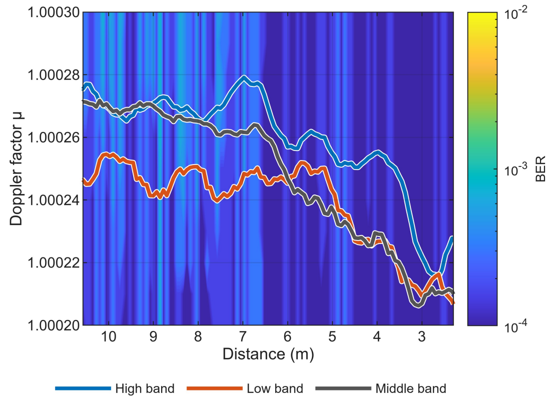

Fig. 12. The relationship between the Doppler factor μ and distance between the transmitter and receiver for different bands of 7 pilots during the transmitter movement speed of 0.5 m/s

The incorrect estimation of the Doppler factor, presented in Fig. 9 in distances between eighth and ninth meters, results from fading in the pilot bandwidth. Figure 11 illustrates pilots in the frequency domain responsible for the symbol with incorrectly estimated Doppler factor. The grayed out area shows the range in which the maximum value was searched, and the vertical dotted lines present the exact frequency on which the pilots were transmitted. The first and third pilots exhibited maximum values near the end of the search area, corresponding to a high Doppler factor suitable for a speed of approximately 1.5 m/s. Whereas, the second pilot was significantly affected by fading, with the maximum value located on the opposite side of the search area, indicating a Doppler factor below 1, corresponding to negative speed. Consequently, this resulted in a low value for the averaged Doppler factor among the 3 pilots.

Figure 12 shows the Doppler factor μ as a function of the distance received with the use of 7 pilots transmitted at different bands during the movement speed 0.5 m/s of the transmitter in the direction of the receiver. As in Fig. 6, the Doppler factor values decrease with distance and the pilots placed in the low band indicated the smallest Doppler factor. Additionally, the fluctuations of the Doppler factor, μ, are significantly lower, than in higher speeds.

The bit error rates displayed in Fig. 13 and Fig. 14 show that at lower speeds, 5 pilots are adequate to ensure reliable estimation of the Doppler factor. In both instances, results obtained with 3 pilots are notably inferior to the others, particularly when utilizing pilots in the low band. However, with 5 pilots and more, this relation reversed, and pilots from the low band exhibited the lowest BER.

VI. Conclusions

To ensure proper wireless transmission for moving objects in highly multipath environments, accurate determination of the Doppler shift at the receiving end of the signal is crucial. The conducted research focused on evaluating the effectiveness of Doppler shift determination using pilots, particularly in terms of selecting the number and frequency of pilots. The study demonstrates that in strong multipath conditions, employing a greater number of pilots diminishes the impact of individual pilot fading, thereby enhancing the accuracy of Doppler shift determination in terms of BER. However, it's important to note that a higher number of pilots concurrently

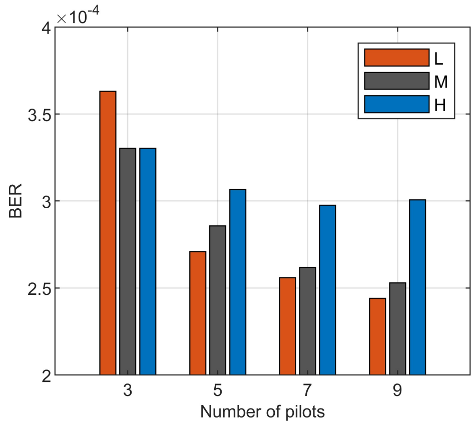

Fig. 13. Averaged BER for different configurations of pilots during the transmitter movement speed of 1.0 m/s.

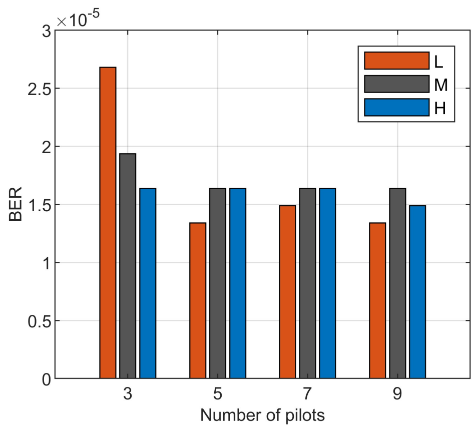

Fig. 14. Averaged BER for different configurations of pilots during the transmitter movement speed of 0.5 m/s.

reduces the available bandwidth for information transmission. The findings of the study suggest that, based on the achieved bit error rate, utilizing 7 pilots positioned at lower frequencies is sufficient. Moreover, it's noteworthy that Doppler factor values associated with the lowest BER did not align with the values calculated from the given speed. Future plans include conducting tests at higher speeds and developing methods for detecting fading in the pilots' bandwidth.

Acknowledgment

The authors would like to thank the Faculty of Mechanical Engineering and Ship Technology of the Gdansk University of Technology for the opportunity to conduct research in the towing tank.

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