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A New Efficient Two-Sided Complementary Code Based Channel Estimation Technique "TSCC-CE" for MIMO-OFDM Systems, Under the Effects of Partial-Band Jamming and Doppler Spread

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ABSTRACT Channel estimation (CE) is a field of study that has garnered much attention during recent years. CE plays an important role in developing channel equalizers. There are many approaches to CE, among which there are orthogonal codes (OC) and orthogonal space-time block codes (OSTBC). Also, complementary codes (CC) have been under investigation for multiple-input, multiple-output orthogonal frequency-division multiplexing (MIMO-OFDM) CE. There are zero side-lobe levels in a CC signal's autocorrelation function. The initial area of application of these signals has been radar systems, and they were used as optimal phase-coding signals. These signals require the use of two different channels to transmit the twofold components of the pilot code. Thus, this research introduces the two-sided CE (TSCE), where separate subcarrier locations are used to carry the two pilot CCs. Equalization errors can occur in dangerous situations, in case a system is interfered with or jammed. This leads to negative impacts on the accuracy of channel estimation. This situation specifically occurs when a harsh Doppler spread is present, as a result of a deterioration in the orthogonality of the subcarriers of the OFDM. Certain conditions were applied for testing the performance of the method suggested in this paper, i.e., the MIMO-OFDM TSCE approach, the method that depends on CCs. These conditions are the Doppler spread, as well as partial-band jamming. Among the different MIMO-OFDM CE techniques, TSCC-CE has shown good performance, with its ability to withstand the effect of partial-band jamming on the accuracy of the MIMO-OFDM CE. This improved performance takes place in the presence of a Doppler spread of moderate value and a partial-band jamming ratio.

INDEX TERMS Complementary codes, two-sided channel estimation, MIMO-OFDM, Doppler shift, partial-band jamming, TSCE, TSCC-CE.

I. INTRODUCTION

Due to its major importance and its constant applications during this era, wireless communication has become a point of focus for researchers. Wireless applications are in constant need of increasing throughput, especially for multimedia files. This has been the reason for the combination between the MIMO system and OFDM modulation, as well as multiuser multiple access techniques. To accomplish this same purpose and to maintain good quality in communication systems, it is also important to maintain the level of interference at a minimum value. An important objective to reach when employing MIMO-OFDM is to conduct synchronization and adaptive equalization. This is done with the help of channel state information (CSI), which also accomplishes the precoding of the transmitting antennas. As such, it can be concluded that CE plays an important role in systems of wireless communication. Basic CE techniques typically employ least squares (LS) and minimum mean square error (MMSE). To estimate CSI, processing in MIMO systems is different and more complicated than processing employed in single-input, single-output (SISO) systems. This is because the former employs a larger number of channel paths linking antennas used in sending and receiving data [1].

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There are two types of CE techniques. The first includes classical techniques, also known as training-based CE techniques. In this type, CSI is reached with the help of previously deduced training symbols or pilots [2]. This type of technique has advantages and disadvantages. The former comes in the form of excellent performance, related to channel estimation error. While the latter can be seen in the higher overhead, resulting from resource usage to accomplish the transmission of pilot signals. The second type of technique is blind CE techniques. This name arises from the fact that they do not use pilot signals. Thus, these techniques use received data symbols and a channel's statistical information to reach CSI [3], [4]. These techniques can only be used in slowly time-varying channels, a drawback accompanied by another in the form of lower estimation performance, i.e., high complexity operation, resulting from the long duration of data recording. These drawbacks are counterbalanced by the techniques' limited overhead.

Training-based CE techniques work by extracting a channel's parameters from the received version of a pilot signal, sent and propagated through the channel. For an accurate CE, pilot signals employ pseudorandom (PN) codes, such as Barker codes and M-sequences with sharp autocorrelation functions [5]. Each of these methods has a certain disadvantage that adds a drawback to classical CE techniques. For instance, Barker codes have a limited length, while M-sequences have relatively high side-lobe levels.

Classical pilot-based CE techniques can also be classified into single-sided CE (SSCE) and two-sided CE. The first employs a single sequence as a pilot signal, while the second employs two sequences. From a general point of view, the performance of TSCE techniques is much better than that of SSCE [6]. However, in the presence of Doppler spread and interference, the performance of TSCE is much affected [7].

Different jamming attacks, a type of adversarial presence, are the conditions applied in the paper during the performance of CE. Much research has focused on jamming scenarios in wireless communication [8]–[10]. A jamming attack of a simple nature is *barrage jamming*. To accomplish this type of attack, the adversary sends a signal that looks much like additive white Gaussian noise (AWGN), jamming the target (data signals) [11]. This type of attack leads to a degraded SNR for the target, caused by an increase in the noise level at the receiver's end. These pilot signal attacks can only take place on a pilot signal, thus the nomenclature. As such, the adversary has to have the information that pilot signals are being employed [12]–[14]. Synchronization must take place between the jammer and the target in pilot signal attacks. On another note, for wireless bands, barrage attacks, as an example of wide-band jamming where the energy used for the attack is transmitted across a wide band, is not as effective as narrow-band jamming (e.g., narrow signal attacks), with energy focused on the subcarriers of the pilot signal. *Singularity attacks* are an alternative type of jamming attacks. During this type of attack, the jammer works on forcing the estimated channel, on the side of the receiver, to reach zero or to be as close as possible to zero [15], [16]. For a singularity attack to work, the jammer needs to know the jammed channels very well. In this case, this type of attack can be highly effective than other types.

The CE technique proposed in this paper was tested on a 2 × 2 MIMO-OFDM wireless system, under the following conditions: the presence of both Doppler spread and adversarial jamming. CCs, with zero side-lobe levels in their autocorrelation function, and TSCE form the basis of this new technique. Placing the two pilot CCs at different subcarrier locations was performed during the application of TSCE in this research. CC optimum correlation properties help in clearly estimating the channel when the pilot CCs are correctly distributed over two antennas and on two consecutive time slots. Even though this paper takes a look at the same issue (techniques used in MIMO-OFDM channel estimation) as other research [17], it focuses on a different scenario with different conditions, i.e., the application of Doppler spread and jamming attacks on the channel under-estimation.

The paper is organized as follows: in Section II, the used MIMO-OFDM communication system model and LS channel estimator are explained. Next, a comparison between PN codes and CCs are presented in Section III. The proposed TSCE using CCs is given in Section V. Simulation results are shown in Section VI. Finally, conclusions are drawn in Section VII.

Notations: Subscript H will be used to denote Hermitian transpose, and * will be used for complex conjugates. We will be using $\varepsilon\{.\}$ for expectation. Also, we will reserve ©for correlations.

II. SYSTEM MODEL AND CHANNEL ESTIMATION

Fig. 1.a illustrates the MIMO-OFDM communication system with N_t transmit antennas, Nr receive antennas, N_{sc} subcarriers, and k the index of the subcarriers, where $0 \leq k \leq N_{sc}-1$. The conventional OFDM modulator and demodulator were used in this illustration. Assume that $\boldsymbol{X^r}[k]$ is the transmitted OFDM symbol from the r$^{\text{th}}$ antenna at a specific time and is denoted by the ($N_{sc} \times 1$) vector. Before transmission, this vector was processed by an inverse discreet Fourier Transform (IDFT) and a cyclic prefix of length larger than the maximum length of all channels. After removing the cyclic prefix at the *qth* reception antenna, we obtain the ($N_{sc} \times 1$) vector $\boldsymbol{Y}^q[k]$, which can be expressed as follows

$$\boldsymbol{Y}^q[k] = \sum\nolimits_{r=1}^{N_t} \mathbf{H}^{r,q}[k]\boldsymbol{X}^r[k] + \sum\nolimits_{i=1}^{N_{tj}} \mathbf{G}^{i,q}[k]\boldsymbol{J}^i[k] + \boldsymbol{\theta}^q, \quad (1)$$

where, $\boldsymbol{J}^i[k]$ is the jamming signal, which is denoted by the (Nsc × 1) vector and corresponds to the i^{th} jamming transmission antenna. The jamming power is equally distributed on all subcarriers. As for $\boldsymbol{\theta}^q$, it is an additive white Gaussian complex noise (AWGN) signal. $\boldsymbol{H}^{r,q}[k]$ is DFT of the sampled channel impulse response (the sampled frequency response), which corresponds to the r^{th} transmitting antenna and the q^{th} receiving antenna. $\boldsymbol{G}^{i,q}[k]$ is the DFT of the jammer channel impulse response which corresponds to the i^{th} transmitting antenna and the q^{th} receiving antenna. N_{tj} is the number of jamming antennas.

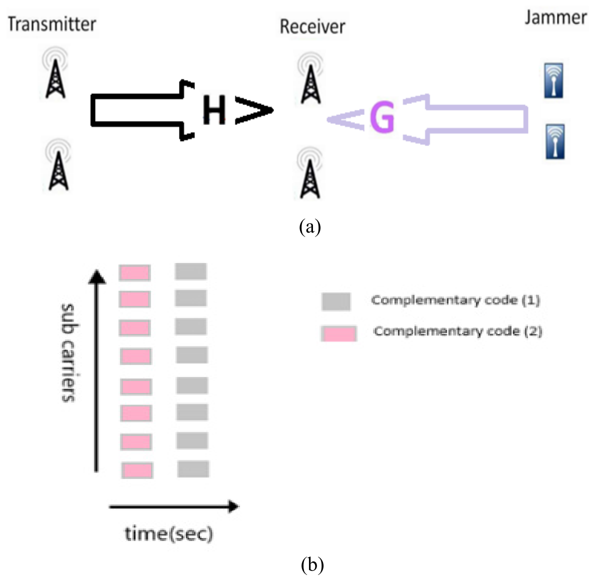

FIGURE 1. a. Jammer and channel estimation b. Code distribution in time and subcarriers.

LS will be introduced in the following section. This is one of the most frequently used linear channel estimators, employed in the assessment of a channel's parameters from the received signal. In the equation describing the LS estimate, H is a deterministic constant. The purpose of this technique/equation is the minimization of the square error, such that

$$\hat{\boldsymbol{H}}^{\mathrm{r,q}} = \left(X^{\mathrm{H}}X\right)^{-1}\mathbf{X}^{\mathrm{H}}\mathbf{Y}^{\mathrm{q}}, \tag{2}$$

Matrix X must abide by an important condition, i.e., it has to be a full column. This means that all of its column vectors must be linearly independent. This implies that, at the position of the transmission antennas, all pilot signals must be linearly independent. Thus, the mean squared channel estimation error can be described as in the equation to follow

$$\mathrm{MSE} = \frac{1}{\textit{rank of the matrix}}\,\boldsymbol{\varepsilon}\left\{\left|\hat{\mathbf{H}}^{\mathrm{r,q}} - \mathbf{H}^{r,q}\right|^{\mathbf{2}}\right\}, \tag{3}$$

When the number of channel taps (L) is multiplied by the number of transmission antennas, the result is the rank of the matrix.

III. CHANNEL ESTIMATION USING PN AND CC CODES

In training-based CE techniques, CSI can be estimated with the help of pilots. In this section, we compare the use of PN and CC codes as pilots for CE.

A. CHANNEL ESTIMATION USING PN CODES

As shown in Appendix (A) (equation A.3), using PN codes with impulsive correlation function can be used to estimate the channel state information (CSI) directly.

The drawback of this method is the non-ideal characteristics of available PN codes (high side lobe correlation) which results in errors in the CE.

So, the proposed technique uses CCs, which have an impulsive ACF as described in the next subsection.

B. CHANNEL ESTIMATION USING CC CODES

As shown in Appendix (B) (equation B.2), the correlation sum of the complementary code pair is impulsive (with no side lobes), and hence as shown in equation (B.3), the output is directly proportional to the impulse response of the channel.

CC's optimum correlation properties help in clearly estimating the channel impulse response *h(t)*.

In our suggested technique, we implement this method by using a space-time block code (STBC).

IV. THE NEW PROPOSED TWO-SIDED CHANNEL ESTIMATION TECHNIQUE USING CCs

The focus of this section is on the newly suggested technique, i.e., the two-sided channel estimation technique, which employs CCs. Complementary code sequences are considered as per the following, without loss of generality:

$\boldsymbol{c_1}\,(\boldsymbol{t})$

$= [+, +, -, -, -, +, -, +, +, +, +, +, -, +, +, -]$ and,

$\boldsymbol{c_2}\,(\boldsymbol{t})$

$= [+, +, -, -, -, +, -, +, -, -, -, -, +, -, -, +]$

These sequences are designed in the frequency domain using the Discrete Fourier Transform (DFT) of complementary codes.

By applying (DFT) to equation (B.2), the result is

$$|C_1(k)|^2 + |C_2(k)|^2 = 2N_c \tag{4}$$

The advantage of designing the pilot sequence in the frequency domain lies in the fact that the sequence is carried by orthogonal sub-carriers. The relative magnitudes of these sub-carriers change because each sub-carrier, upon passing through the channel, is multiplied by the corresponding value of the channel frequency response at that frequency.

However, with the assumption that the guard interval is longer than the maximum length of the sampled channel impulse response L, the sub-carriers remain orthogonal at the receiver, and we can recover the pilot sequence without any interference.

Now let us define matrix A as

$$A = \begin{bmatrix} C_1^*[k] & C_2^*[k] \\ -C_2^*[k] & C_1[k] \end{bmatrix}, \tag{5}$$

which satisfies,

$$\begin{bmatrix} C_1[k] & -C_2^*[k] \\ C_2[k] & C_1^*[k] \end{bmatrix}\begin{bmatrix} C_1^*[k] & C_2^*[k] \\ -C_2^*[k] & C_1[k] \end{bmatrix} = \begin{bmatrix} 2N_c & 0 \\ 0 & 2N_c \end{bmatrix} = 2N_c\mathbf{I}, \tag{6}$$

where $\mathbf{I}$ is the identity matrix.

These properties of CC will be central to the idea of channel estimation presented in the next section.

To estimate different channels, the received sequences are multiplied by Matrix A. These signals are received over two different antennas, in two different time slots. The result of this multiplication is

$$\mathrm{R}(k)A(k) = \begin{bmatrix} Y_{11}[\mathrm{k}] & Y_{12}[\mathrm{k}] \\ Y_{21}[\mathrm{k}] & Y_{22}[\mathrm{k}] \end{bmatrix} \begin{bmatrix} C_1^*[k] & C_2^*[k] \\ -C_2^*[k] & C_1[k] \end{bmatrix} = 2N_c \begin{bmatrix} H_{11}[k] + \frac{\beta_1}{2Nc} & H_{21}[k] + \frac{\beta_2}{2Nc} \\ H_{12}[k] + \frac{\beta_3}{2Nc} & H_{22}[k] + \frac{\beta_4}{2Nc} \end{bmatrix}, \tag{7}$$

where,

$$Y_{11}[k] = H_{11}[k]C_1[k] + H_{21}[k]C_2[k] + G_{j1,1}[k]J_1[k] + G_{j2,1}[k]J_2[k] + \theta^1, \tag{8}$$

$$Y_{12}[k] = H_{11}[k]\left(-C_2^*[k]\right) + H_{12}[k]C_1^*[k] + G_{j1,1}[k]J_3[k] + G_{j2,1}[k]J_4[k] + \theta^2, \tag{9}$$

$$Y_{21}[k] = H_{21}[k]C_1[k] + H_{22}[k]C_2[k] + G_{j1,2}[k]J_1[k] + G_{j2,2}[k]J_2[k] + \theta^3, \tag{10}$$

$$Y_{22}[k] = H_{21}[k](-C_2^*[k]) + H_{22}[k]C_1^*[k] + G_{j1,2}[k]J_3[k] + G_{j2,2}[k]J_4[k] + \theta^4, \tag{11}$$

$$\beta_1 = \{G_{j1,1}J_1C_1^* + G_{j2,1}J_2C_1^* + \theta^1C_1^* + G_{j1,1}J_3C_2^* + G_{j2,1}J_4C_2^* + \theta^2(C_2^*)\}, \tag{12}$$

$$\beta_2 = \{G_{j1,1}J_1C_2^* + G_{j2,1}J_2C_2^* + \theta^1C_2^* + G_{j1,1}J_3C_1^* + G_{j2,1}J_4C_1^* + \theta^2(C_1^*)\}, \tag{13}$$

$$\beta_3 = \{G_{j1,2}J_1C_1^* + G_{j2,2}J_2C_1^* + \theta^3C_1^* + G_{j1,2}J_3C_2^* + G_{j2,2}J_4C_2^* + \theta^4(C_2^*)\}, \tag{14}$$

$$\beta_4 = \{G_{j1,2}J_1C_2^* + G_{j2,2}J_2C_2^* + \theta^3C_2^* + G_{j1,2}J_3C_1^* + G_{j2,2}J_4C_1^* + \theta^4(C_1^*)\}, \tag{15}$$

J_1 *and* J_2 are the jamming signal from antenna 1 and antenna 2 at time index 1, respectively, while $J3$ and $J4$ are the jamming signal from antenna 1 and antenna 2 at time index 2, respectively. In addition, G*j1,1*, G*j2,1*, G*j1,2*, G*j2,2* are the jamming channel coefficients from the jammer antennas to the receiver as shown in Fig. (1. a).

V. EFFECT OF THE PARTIAL-BAND JAMMING RATIO

A jammer may increase the degradation in a communication system by employing partial band jamming. So let us define a parameter, ρ, where $0 < \rho \leq 1$, representing the fraction of the band being jammed as shown in equation (16), where (Wj) represents the jammed subcarriers, and N_{sc} represents the total number of subcarriers. An intelligent jammer with fixed finite power can produce significantly greater degradation with partial band jamming than is possible with broadband jamming.

$$\rho = \frac{\mathrm{W_j}}{\mathrm{N_{sc}}}, \tag{16}$$

So, we define another measurement of performance, which is the performance of the MSE of the channel estimation over the partial band jamming ratio (PBJR). The PBJR is considered as the jammed subcarriers over the total subcarriers.

VI. SIMULATION RESULTS

This section shows the performance of a channel estimation technique based on mean square error (MSE). This takes place for a 2 × 2 MIMO-OFDM system constituted of $N_{sc} = 16$ subcarriers and a Rayleigh channel. In this system, the Doppler shift (Ds) is defined as the shift in radio frequency, caused by the movement of the transmitter or the receiver. One of the parameters of the Doppler shift is coherence time (Tc), which can be calculated as per the following

$$T_c = \frac{1}{4D_s}, \tag{17}$$

The channel is said to be time-varying, should the coherence time (T_c) be comparable to the symbol period. If T_c is much bigger than the symbol period, then the channel is time-invariant (i.e., it remains constant). Operating frequency, described in the equation below, is shifted by the Doppler effect.

$$f'_k = \mathrm{a} f_k \tag{18}$$

where, f_k is the operating frequency of a k subcarrier. As for (a), it is the Doppler scaling factor, a figure that is constant for all subcarriers. The constant Doppler scaling factor (a), whose values are given by 0.02 and 0.01 in this case study, was studied for all subcarriers.

To conduct these simulations, complex Gaussian channels, having binary phase-shift keying (BPSK) modulation, were used. A random selection, run 16 times, was carried out to choose the subcarriers to be jammed from all available subcarriers. The 16 repetitions were performed so that as many subcarriers as possible can be chosen for performing the prescribed tests. As an example, the first round of simulations had four subcarriers, which were selected on a random basis. This process was repeated 16 times so that a larger number of subcarriers is covered. The average of the 16 cases was then calculated. The same process was repeated for 8 and then 10 subcarriers, etc. For comparison purposes, another technique for channel estimation was performed. It applies SSCE with orthogonal codes [17], [19].

For the newly proposed technique, the sequence was distributed in the form of blocks. Each of these blocks was either CC 1 or CC 2, distributed on antennas (1) and (2). In Fig. 1. b, these CCs are drawn on the Y-axis against two dimensions of time (measured in seconds) on the X-axis.

For the suggested TSCE technique and Orthogonal Codes (OCs), the mean squared error at SNR for the average of four jammed subcarriers, for (a) = 0.01 and 0.02 can be seen in Fig. 2. From this Figure, it can be noted that for the suggested technique and under the two chosen values of the Doppler shift factor, the best performance was reached at an SNR of approximately less than 16.5 dB for (a) = 0.01 and

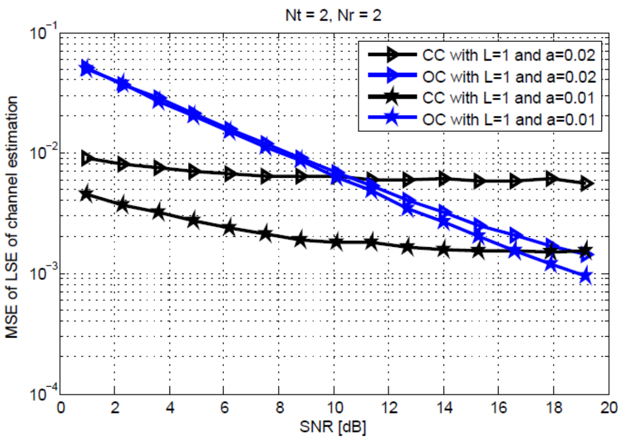

FIGURE 2. MSE with SNR in case of 4 jammed subcarriers, L = 1, a = 0.01 and a = 0.02.

10.1 dB. for (a) = 0.02. As can be seen in Fig. 3, the best performance for the suggested TSCE technique can be seen under the following conditions: (a) = 0.01 and the number of channel taps = 2. On the other hand, for an (a) of 0.02, better performance could be witnessed for L = 1, at an SNR of approximately less than 13 dB. As for L = 2, the best performance was seen at SNR $\leq$ 15 dB. It is important to note that in the case of OCs and at low SNR, jamming had a major influence on the subcarriers' orthogonality because the jammer can destroy the orthogonality of these OCs. On the other hand, at high values of SNR, the OC technique yielded better results.

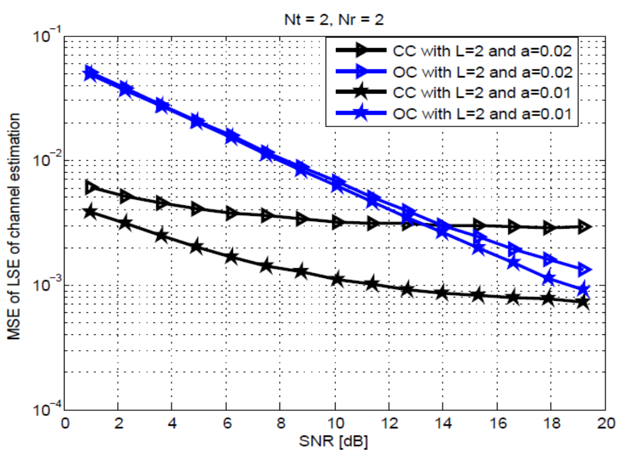

FIGURE 3. MSE with SNR in case of 4 jammed subcarriers, L = 2, a = 0.01, and a = 0.02.

The MSE for the LS channel estimation technique can be seen in Fig. 4, which is plotted against the jamming-to-signal ratio (JSR). This took place under these conditions: SNR = 15 dB., (a) = 0.02, and L = 1. The best performance, in this case, was achieved with eight average jammed subcarriers, with JSR from -7 to 20 dB. From Fig. 5, it could be seen that a significant improvement was witnessed between JSR −10 and 20 dB for a multipath ray channel (L) = 3.

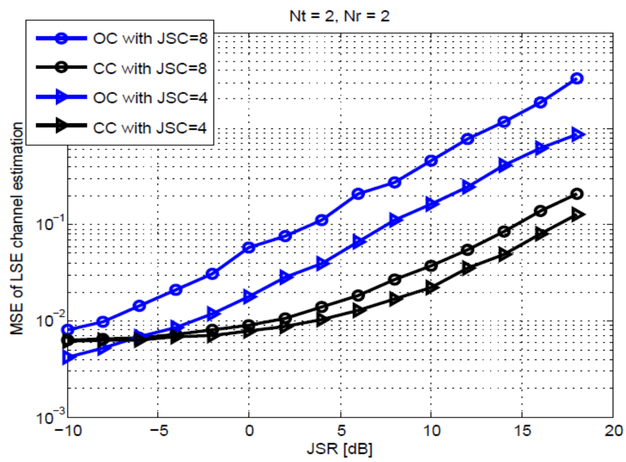

FIGURE 4. MSE with JSR in case of L = 1, a = 0.02, and 4, 8 jammed subcarriers.

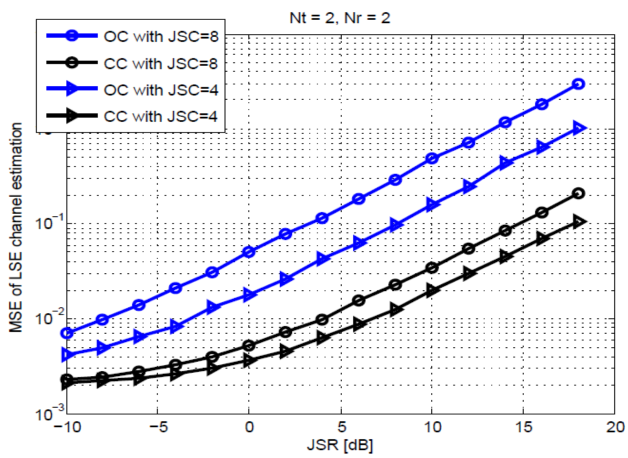

FIGURE 5. MSE with JSR in case of L = 2, a = 0.02, and 4, 8 jammed subcarriers.

For PBJR, a random selection of jammed subcarriers was also undertaken 16 times, before an average was calculated. This repetition was performed to cover as many cases of jammed carriers as possible. As an example, in the first case, two jammed subcarriers were chosen at random. This process was repeated 16 times to cover the highest number of subcarriers. Following this step, the average of the 16 cases was calculated. This process was then repeated for four, six, eight, and ten subcarriers, etc.

The performance of MSE of the least square error (LSE) for CE against PBJR, in the case of the proposed technique using the CCs, can be seen in Fig. 6. The results were obtained for SNR = 10 dB, JSR = -2 dB, and L = 1 and 2. In the case of L = 2, the maximum error, which occurred at $\rho\rho = 0.9$ was higher than the maximum error in the case of L = 1. In both cases of channel taps (L = 1 and 2), the slope in the range of $0.9 \leq \rho \leq 0.95$ increased slowly, while in the range of $0.1 \leq \rho \leq 0.9$, the slope decreased fast.

Fig. 7 shows the performance of MSE of LSE for CE against PBJR, in the case of SNR = 10 dB., JSR = −2 dB., and L = 1 and 2. This Figure illustrates the results in the case

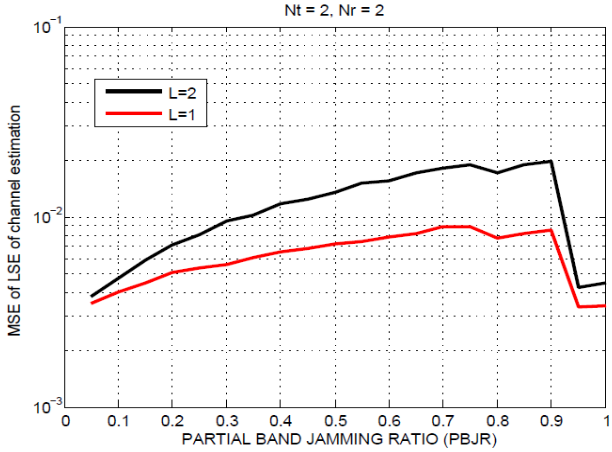

FIGURE 6. MSE with PBJR in case of using CC with SNR = 10 dB., JSR = −2 dB., a = 0.02 and L = 1,2.

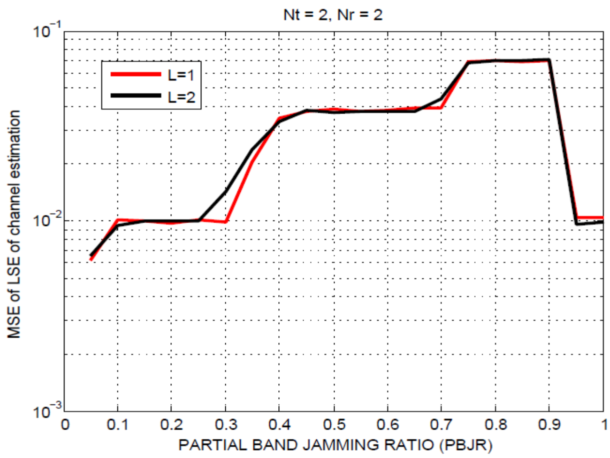

FIGURE 7. MSE with PBJR in case of using OC with SNR = 10 dB., JSR = −2 dB., a = 0.02 and L = 1,2.

of using OCs, where the maximum error in case of L = 1 and 2 was equal and occurred within the range of $0.75 \leq \rho \leq 0.9$. A very important issue to note in Fig. 7 is that the slope in the range of $0.3 \leq \rho \leq 0.4$ increased faster than the slope in the range of $0.6 \leq \rho \leq 0.75$.

VII. CONCLUSION

This paper proposed a new technique for use in channel estimation, based on complementary codes. It is entitled TSCC-CE. Using MATLAB, the performance of this technique was simulated for study and analysis. It was concluded from the simulations conducted that this new method had many advantages when compared to other techniques, specifically the application of orthogonal codes, at low SNR. This presents a great advantage. Zero side-lobe levels in the autocorrelation function are among the benefits of CCs that this new technique makes use of.

Upon keeping jamming power at a constant level and with the use of a single path channel at low Doppler shift, the suggested technique outperformed OC-based techniques, for all tested SNR values.

With a higher Doppler spread and low SNR, the suggested technique outperformed techniques depending on OCs. However, at higher SNR (approximately > 10 dB.), the latter techniques performed better than the former, specifically for 4 out of 16 jammed subcarriers.

The conditions leading to the best performance are the use of multipath channels having two or three multipath components and an (a) of 0.01.

In the case of partial-band jamming, it was concluded that as the number of jammed subcarriers decreased, the performance of the new technique increased (i.e., the performance of TSCC-CE depends on the number of jammed subcarriers and the partial-band radio). It looks at the rays in optimum partial band ratio for better performance. This will be the subject of investigation in a subsequent paper.

Channel jamming seems to have a major effect on the performance of the comparable channel estimation techniques of TSCE and OC-based CE. When using eight jammed subcarriers, TSCC-CE underperforms OC. However, the former technique outperforms the latter, upon the use of four jammed subcarriers.

The proposed technique showed more improved performance over others only for JSR = −7 dB., for a single path channel, four jammed subcarriers, different jamming power, and a constant SNR of 15 dB. On the other hand, for multipath channels having two multipath components, the best performance by TSCC-CE was seen over the whole range of JSR.

One important issue to keep in mind for this technique is that when using orthogonal codes, the jammer can destroy this orthogonality, especially with the effect of the Doppler shift and low SNR.

MSE for PBJR has also been tested using pilots consisting of a pair of complete complementary codes and a pair of orthogonal codes, under the following conditions: SNR = 10, JSR = −2, and L = 1 and 2. For L = 1 and 2 and an (a) = 0.02, the results of the simulations conducted have proven that the maximum error while using CCs was less than the maximum error when using OCs, $\rho = 0.9$ and $0.75 \leq \rho \leq 0.9$, respectively.

The disadvantage of the proposed technique is the losses incurred in data due to the use of two pilots. This results in a slight reduction in data rate, however, the optimum results achieved in channel estimation, resulting in an overall enhancement of the system's performance make up for this disadvantage.

APPENDIX (A)
CHANNEL ESTIMATION USING PN CODES

Pseudorandom (PN) codes, with sharp autocorrelation functions, are used as pilots in many applications. Using PN codes has some disadvantages, such as a limited length of Barker codes. While, On the other hand, M-sequences, although have no length limitations, have relatively high correlation sidelobe levels.

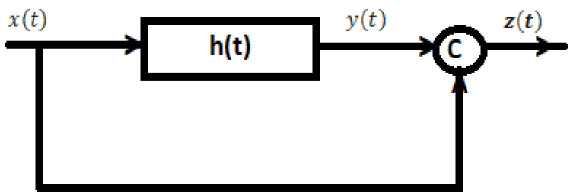

FIGURE 8. Overall communication system in case of PN codes.

In this Appendix, we describe and analyze the use of PN codes in CE. As shown in Fig. 8, the received sequence can be expressed as

$$z(t) = h(t) * R_x[t] \tag{A.1}$$

where, $Rx[\tau]$, h(t), and $z(t)$ are autocorrelation function (ACF) of the PN code, channel impulse response, and estimated channel impulse response, respectively. Ideally, a sequence with the following impulsive correlation is required

$$R_x[t] = N_c\delta(t) \tag{A.2}$$

where N_c is the length of the code.

In this case, it is quite simple to reach the channel impulse response from the received signal, such that

$$z(t) = h(t) * N_c\delta(t) = N_c h(t) \tag{A.3}$$

However, it is difficult to get a PN code with an impulsive ACF. So, the proposed technique uses CCs, which have an impulsive ACF.

APPENDIX (B)
CHANNEL ESTIMATION USING CCs

CCs, with zero side-lobe levels in their ACF, form the basis of this new technique. Placing the two pilot CCs, $c1(t)$ and $c2(t)$, at different locations was performed as shown in Fig. 9.

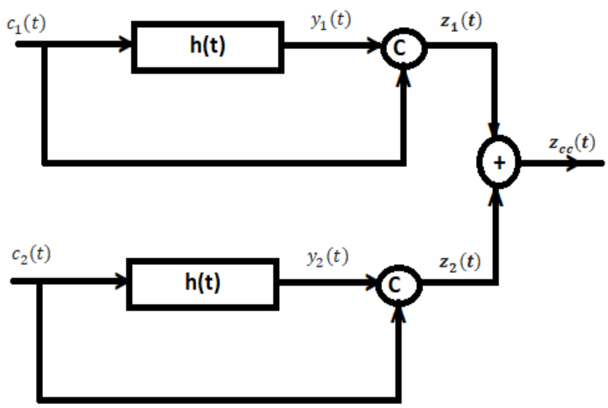

FIGURE 9. Overall communication system in case of CC.

The estimated channel impulse response (CIR), in this case with the assumption of the quasistatic channel, is

$$z_{cc}(t) = h(t) * \left[R_{c1,c1}[t] + R_{c2,c2}[t]\right] \tag{B.1}$$

where, $R_{c1,c1}[t]$ is the ACF of the first code, while $R_{c2,c2}[t]$ is the function for the second code. One of the properties of CCs is that the summation of the ACFs of the first and second codes will yield a Dirac-delta function.

$$R_{c1,c1}[t] + R_{c2,c2}[t] = 2N_c\delta(t) \tag{B.2}$$

where N_c is the length of the code.

Then, we can benefit from this property in estimating the channel, such that

$$z_{cc}(t) = 2N_c h(t) \tag{B.3}$$

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