

# A NOVEL ROBUST AND LOW-COMPLEXITY SPACE-TIME CODES FOR INDUSTRY 4.0 SYSTEMS

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## ABSTRACT

*This paper proposes different robust and low-complexity space time codes which provide more reliability for industrial automation. An innovative synchronized uplink system configuration for an Industrial Environment is proposed. Mathematical framework for estimating the channel phase of each Slave Node (SN) is developed. Furthermore, the channel is practically estimated based on an innovative method using parallel sequence spread spectrum (PSSS) implemented in Universal Software Radio Peripheral (USRP). The proposed space time codes are applied in the uplink of an industrial communication system where the channel is modelled using Quasi Deterministic Radio Channel Generator (Quadriga) which follows a geometry-based stochastic approach. Simulation results exposed that the proposed codes surpass Alamouti code for Industrial Automation. The bit error rate (BER) performance demonstrates that the achieved coding gain for the proposed codes is higher than Alamouti code leading to more robust communication. Furthermore, a low complexity decoders based on minimum mean squared error (MMSE) and zero forcing (ZF) algorithms are designed at the receiver side. The proposed codes give a predominant execution against the state-of-the-art space time codes for Industry 4.0.*

## KEYWORDS

*Industrial Communication, Space-Time Code, Quadriga, Minimum Mean squared Error decoder, Zero Forcing Algorithm, Parallel Sequence Spread Spectrum, Software Defined Radio, Factory Automation.*

## 1. INTRODUCTION

Lately, the recent advances of wireless communication technology have gained much more attention to be applied into industrial applications, more specifically, in Wireless Sensor Networks (WSN) [1]. Industrial wireless communication is expected to provide a high degree of real time dynamic control for industrial processes. In addition, the inherent flexibility and the retrofitting ability of wireless technologies offer a great potential for the future of industrial communication [2].

Industry 4.0 is a German approach to implement new technologies in the manufacturing process. It is also called as Smart Factory (SF) [3]. Industrial radio is an important research track within the German research programs on Industry 4.0 [4]. In general, Factory Automation (FA), Process Automation (PA) and Condition Monitoring (CM) are the basic three categories of industrial applications [2]. Factory Automation (FA) is the most demanding sector in terms of high reliability and low latency with moderate requirements regarding the number of nodes and complexity of topology [5].

Moreover, the state-of-the-art wireless technology could not face the challenges of the harsh channel conditions in industrial environments to achieve the demanded robustness of the

communication. The industrial environments are filled with metal structure of pipes, pumps and robots besides different kinds of machines [6]. Therefore, the industrial channel is basically characterized as highly scattering environment. In addition, the nodes can be shielded by the metal structures in a specific direction for a specific time. This results in significantly deteriorating the performance.

On one hand, to achieve high reliability using MIMO techniques, spatial diversity can be the optimum solution. Specifically, space time code can effectively exploit the spatial diversity created by multiple signal transmission [7-8]. The diversity order and the coding gain achieved by the space time code provide the optimal approach for fulfilling the reliability demands of Industry 4.0.

On the other hand, distributed antennas can upgrade both the energy efficiencies and spectrum effectively [9]. In Distributed Antenna system (DAS), the antennas are distributed over the service region and connected to a baseband unit (BBU) [10]. This structure helps significantly in improving the received signal. Many research papers have studied the potential of DAS based on perfect knowledge of Channel State Information (CSI) at the transmitter [11-13]. However, to the best knowledge of the authors, none of research studies has investigated the performance of Distributed Antenna system (DAS) combined with space time code into Industrial Automation. This research area is of a great concern for standardization of industry 4.0.

In this paper, the system configuration for Industrial communication from Uplink (UL) perspective is addressed. The configured system is based on a distributed structure for the antennas of the Master Node (MN) to achieve Line of Sight (LoS) for the Slave Nodes (SNs). The slave nodes are assumed to be equipped with two antennas such that space time code (STC) can be applied. An innovative approach of estimating the channel phase between each SN and MN will be provided. Mathematical framework for adjusting the phase of the transmitted signal from the collaborating nodes will be developed. A novel robust space time codes are proposed such that a high reliability can be achieved in the industrial environment. Furthermore, the decoding process is performed using low complexity linear decoders based on Minimum Mean Squared Error (MMSE) and Zero Forcing (ZF) algorithms. Therefore, the complexity of the proposed space time codes is lower than the others STC systems. The proposed space time coding schemes will be compared with the widely adopted Alamouti scheme and the overall performance will be investigated in terms of BER and its benefit on increasing the reliability of industrial automation significantly and the communication quality in general.

The rest of the paper is organized as follows: in section II, Industrial communication system model will be developed. The proposed space-time block code will be presented in section III. Section IV presents the implementation of PSSS based channel measurements using SDR. The simulation results will be presented in section V. Conclusion will be provided in Section VI.

## 2. SYSTEM MODEL

Figure 1 illustrates the proposed uplink system model for a factory hall of spatial dimension  $20 \times 20 \times 10$ . The slave nodes are uniformly distributed over the factory hall region. It is assumed that the Master Node (MN) is connected by high speed and capacity link to distributed antennas (DAS) such that the distributed antennas are perfectly synchronized to each other. The number of distributed antennas which connected to the master node is assumed to be 4. In this paper, the slave nodes are assumed to be equipped with two antennas and be collocated in the centre of the factory hall such that each node is at an approximate distance of  $10\sqrt{2}$  m from the slave nodes. It is assumed that the total number of MN antennas is  $N_m$  and K Slave nodes.

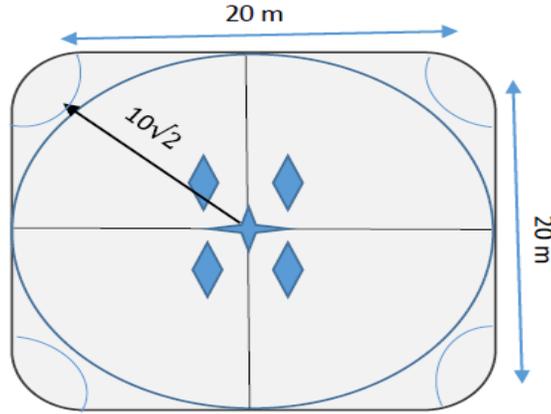


Figure 1. The proposed system model for a factory hall

## 2.1. CHANNEL MODELLING OF INDUSTRIAL WIRELESS SYSTEM

The wireless channel in industrial environments has a different statistical analysis in comparison to the free space urban area. The factories have concrete floors and metal ceilings. Moreover, building walls are made of thick concrete [14]. This is anticipated to lead to severe multipath. Therefore, the industrial wireless channel is better represented by Saleh-Valenzuela Model with modifying its parameter. In this paper, for realistic channel model to accurately estimate the performance of industrial communication, Quadriga channel modelling has been used. Quadriga channel model follows a geometry-based stochastic channel modeling approach. The industrial channel is represented by distance dependent pathloss, log normally distributed shadowing loss and Nakagami-m multipath fading. Table I presents the assumed parameters for industrial channel which is compiled from several research studies [7, 14-15].

Table I. Parameters Of Industrial Channel Small Scale Fading

Mean number of clusters	6.75
Inter-Cluster arrival rate [1/ns]	0.0709
Cluster shadowing variance	5.45
Nakagami-m factor mean	0.36 dB
Nakagami-m factor variance	1.13

Each channel is represented by a number of multipath components enriched by the scattered industrial environment. The channel impulse response between the  $j^{\text{th}}$  transmit antenna and the  $k^{\text{th}}$  receive antenna at the carrier frequency  $f_c$  is modeled as [16]

$$g_{kj}^n(t) = \sum_{c=1}^{P_T} \sqrt{P_c} \cdot e^{j\theta_c} \cdot \delta_c(t - \tau_c) \quad (1)$$

where  $P_c$ ,  $\theta_c$ , and  $\tau_c$  are the received power, the phase angle and the time delay of the  $c^{\text{th}}$  path, respectively.  $P_T$  is the total number of paths, and  $\delta_c$  is the delta impulse function. The frequency response between the  $j^{\text{th}}$  transmit antenna and the  $k^{\text{th}}$  receive antenna at the carrier frequency  $f_c$  can be calculated as [17]

$$h_{kj}^n = \sum_{c=1}^{P_r} \sqrt{P_c} e^{j\theta_c} e^{j2\pi f_c \tau_c} \quad (2)$$

where  $f_c$  is the carrier frequency. In this paper, the carrier frequency is chosen to be 5.8 GHz which is the nominal used frequency for industrial applications [18].

The channel coefficients between the  $K^{\text{th}}$  transmit antenna and the  $j^{\text{th}}$  receive antenna is denoted as  $H_j$ , where  $H_j = \frac{1}{(d_j/d_0)^{\alpha/2}} h_{kj}$ ,  $\alpha$  is the path-loss exponent and  $d_0$  is the reference distance [19].

In our paper, the path-loss exponent is chosen to be 2.5, as the path-loss in obstructed industrial environments ranges between 2 to 3 [20].

## 2.2. MATHEMATICAL FRAMEWORK FOR CHANNEL PHASE ESTIMATION

Instead of estimating the whole RF channel, it is required only to estimate the change in the phase of the channel during the propagation. Therefore, the communication between one SN and the MN's distributed antennas is considered. In such scenario, the distance between SN  $i$  and  $j$  MN antenna is  $d_{ji}$ . The channel phase can be estimated as

$$\phi_{ji} = -2\pi f t_{ji} = -2\pi \frac{c}{\lambda} t_{ji} = -2\pi \frac{d_{ji}}{\lambda} \quad (3)$$

Where  $\lambda$  is the wavelength of the signal.

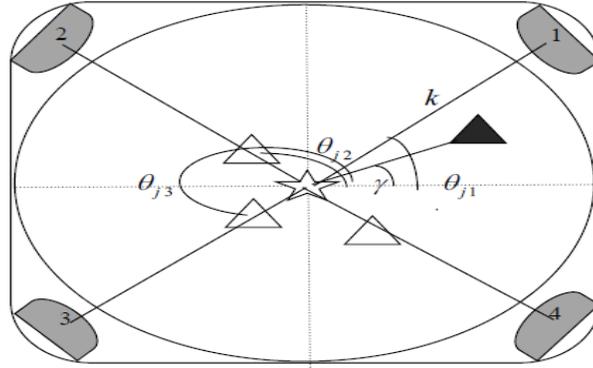


Figure 2. Channel Phase Estimation.

As in the factory, the distance between each SN and MN antennas are well known and has been measured. In case of closely collocated SNs, Centralized Core Node (CCN) can be chosen randomly and the distance between the centralized core node and SN is measured such that the estimated phase is:

$$\phi_{ji} = -\frac{2\pi}{\lambda} k [\cos(\theta_{j1} - \gamma) + \cos(\theta_{j2} - \gamma) + \cos(\theta_{j3} - \gamma) + \cos(\theta_{j4} - \gamma)] \quad (4)$$

Where  $\theta_{j1}$  is the angle between centralized core node and the distributed antenna 1.  $\gamma_i$  is the angle between the centralized core node and transmitted SN.  $k$  is the distance between the

centralized core node and the distributed antennas. The distance is constant with regard to the centralized core node because of the proposed distributed geometry.

### 2.3. PSSS BASED CHANNEL STATE MEASUREMENT

In order to achieve coherent constructive combining of the signals from SNs to MN, the channel phase distortion need to be efficiently estimated. Industrial communication demands short latencies and high reliability. Recently, there are many research studies to investigate the feasibility of Parallel Sequence Spread Spectrum (PSSS) to fulfil such requirements. Cyclical shift of a base m-sequence is the basis for PSSS operation. This is very similar to Direct Sequence Spread Spectrum (DSSS), as in DSSS with an appropriate sequence data symbols are spread. Our approach to estimate the channel between each SN and MN is based on that each SN utilizes a unique cyclically shifted m-sequence. In PSSS the data symbols are distinguished by an exclusively assigned cyclic shift of a base sequence  $m_{\rightarrow 0}$ . A general description of PSSS for m-sequences of variable length is given in [21]. PSSS is part of IEEE 802.15.4-2011 [22], where PSSS is specified for an m-sequence of  $n = 31$  chips. Each SN has its own sequence which is multiplied by a pilot signal of any length. Pilot signal is taken to be of length 1 to reduce the complexity. Figure 3 illustrates the overall channel estimation process using PSSS. Each Pilot symbol  $d_i$  of  $d$  is spread simultaneously with an m-sequence  $m_{\rightarrow i}$ , which is cyclically shifted by  $i$  chips. At the MN, the pilot symbols for each channel are retrieved by cyclic correlation with the assigned sequence to each SN.

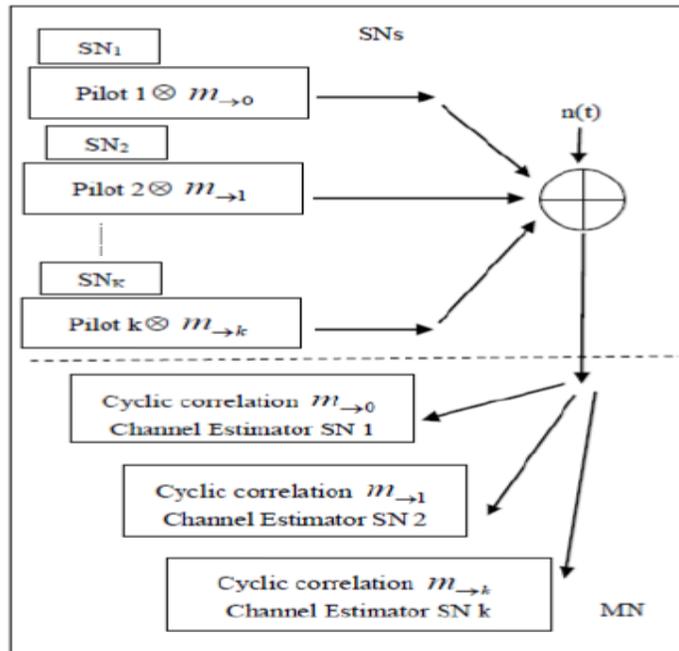


Figure 3. PSSS based channel estimation.

At each SN, the pilot  $k$  is multiplied with the assigned unique code sequence resulting in multi-level PSSS symbol vector  $S$  over the channel as in (5).

$$S = EN .P \quad (5)$$

Where EN is the encoding matrix containing all the cyclically shifted sequences and P is the pilot signals.

At the MN, the cyclic correlation yields the linearly superposed autocorrelation coefficients of the basic m-sequence  $m \rightarrow 0$  and its cyclic shifts, respectively. The autocorrelation of  $m \rightarrow 0$  is given by (6).

$$\phi = m_{\rightarrow 0} \otimes m_{\rightarrow 0} \quad (6)$$

The channel can be effectively estimated based on the result of the cyclic correlation for each SN.

## 2.4. Signal Representation

In this section, the signal representation of the proposed space time code is expressed. Suppose each Slave Node (SN) in the factory adopts STBC to transmit the signal. Denote the code of  $K^{\text{th}}$  SN as  $X_k$  with the size of  $2 \times T$ . The received signal by the MN in T time slots can be expressed as follows:

$$Y = \sum_{k=1}^K \sqrt{\frac{\rho}{2}} H_k X_k + n_k \quad (7)$$

where  $H_k \in \mathbb{C}^{4 \times 2}$  represents the channel fading coefficients from the  $K^{\text{th}}$  SN to MN antennas.  $n_k \in \mathbb{C}^{4 \times 2}$  is a random matrix, whose entries are independent identically distributed (i.i.d) circularly-symmetric complex Gaussian random variables with zero mean and unit variance.  $\rho$  represents the received SNR.  $\sqrt{\frac{1}{2}}$  is used to normalize the transmitted signal energy to be 1 in each time slot.

## 3. THE PROPOSED SPACE-TIME CODING SCHEMES

In this section, the proposed coding schemes for the transmitted signal from the SN to MN for industrial Automation is presented. Then, a near optimal, low-complexity linear decoder to estimate the transmitted signal at MN, considering the case of one SN with two transmitting antennas is designed. Firstly, let  $X_k$  is the transmitted signal from the two transmit antennas at SN over T time slots, where  $X_k \in \mathbb{C}^{2 \times T}$ . In this paper, T=2 is chosen.

**Proposition 1:** The corresponding space-time code is designed as follows, i.e.

$$X_k = \begin{pmatrix} as_1 - cs_2 & ds_1^* - bs_2^* \\ bs_1^* + ds_2^* & cs_1 + as_2 \end{pmatrix} \quad (8)$$

where  $s_1$  and  $s_2$  are the transmitted symbols over 2 Time slots leading to achieve a code rate of 1. Here \* indicates complex conjugate. These symbols are generated using a QAM constellation. a, b, c and d are complex valued-design parameters to be defined later.

Let us consider the equivalent channel from one SN to MN  $H_k = [h_{k1} \ h_{k2}]$ . It is assumed that the channel coefficients are quasi-static such that they do not change with respect to time over the coding block period.

By substitution, equation (7) can be rewritten as follows:

$$Y = \sum_{k=1}^K \sqrt{\frac{\rho}{2}} H_k X_k + n_k \quad (9)$$

where  $H_k = \begin{pmatrix} ah_{k1} & -ch_{k1} & bh_{k2} & -dh_{k2} \\ ch_{k2} & ah_{k2} & dh_{k1} & bh_{k1} \end{pmatrix}$  and  $X_k = [s_1 \ s_2 \ s_1^* \ -s_2^*]^T$ .

The orthogonality of the proposed code is achieved as it satisfies  $XX^H = \alpha I$  ;

$$\begin{aligned} XX^H &= \\ & \begin{pmatrix} as_1 - cs_2 & ds_1^* - bs_2^* \\ bs_1^* + ds_2^* & cs_1 + as_2 \end{pmatrix} * \begin{pmatrix} as_1^* - cs_2^* & bs_1 + ds_2 \\ ds_1 - bs_2 & cs_1^* + as_2^* \end{pmatrix} \\ &= ((as_1 - cs_2)^2 + (ds_1 - bs_2)^2 + \\ & (bs_1 + ds_2)^2 + (cs_1 + as_2)^2) \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \end{aligned} \quad (10)$$

The used constraint to design this STC is the transmission of equal average power for each symbol time such that  $|a|^2 + |d|^2 = |c|^2 + |b|^2 = 1$ . This constraint allows us to simplify the optimization procedure to determine the parameters a, b, c and d.

The proposed space time code  $X_k$  in equation (8) is a maximum likelihood (ML) detectable with exhaustive search complexity  $O(M^2)$ , where M is the constellation size. The exhaustive search makes a search over all possible values of the transmitted symbols ( $s_1, s_2$ ) and decides in favour of ( $s_1, s_2$ ) which minimizes the Euclidean distance  $D(s_1, s_2)$ .

$$\begin{aligned} D(s_1, s_2) &= \sum_{k=1}^{N_r} \left| y_{k1} - h_{k1}(as_1 - cs_2) - h_{k2}(bs_1^* + ds_2^*) \right|^2 \\ &+ \sum_{l=1}^{N_r} \left| y_{l2} - h_{l1}(ds_1^* - bs_2^*) - h_{l2}(cs_1 + as_2) \right|^2 \end{aligned} \quad (11)$$

By expanding  $D(s_1, s_2)$ , equation (11) can be rewritten as follow:

$$\begin{aligned}
 D(s_1, s_2) = & C + g(s_1, s_2) + \\
 & \sum_{k=1}^{N_r} 2\Re\{h_{k1}h_{k2}^*(ad^*s_1s_2 - cb^*s_2s_1 - ab^*|s_1|^2 - cd^*|s_2|^2)\} + \\
 & \sum_{l=1}^{N_r} 2\Re\{h_{l1}h_{l2}^*(da^*s_1^*s_2^* - ba^*|s_2|^2 + dc^*|s_1|^2 - bc^*s_2^*s_1^*)\}
 \end{aligned} \tag{12}$$

where  $C$  is a constant independent of the symbols and  $g(s_1, s_2)$  is a function of the symbol pair  $(s_1, s_2)$ . To minimize the Euclidean distance, one may choose  $|a| = |d| = \frac{1}{\sqrt{2}}$ . In order to set the values of the other parameters, one may perform exhaustive search for maximizing the coding gain. From the set of values, the following parameter pair have been chosen.

$$\begin{aligned}
 b &= (1 - \sqrt{7}) + \frac{i(1 + \sqrt{7})}{4\sqrt{2}} \\
 c &= \frac{1 + i\sqrt{7}}{4}
 \end{aligned} \tag{13}$$

**Proposition 2:** The corresponding space-time code is designed as follows, i.e.

$$X_k = \begin{pmatrix} as_1 - cs_2 & ds_1^* + bs_2^* \\ bs_1^* - ds_2^* & cs_1 + as_2 \end{pmatrix} \tag{14}$$

where  $s_1$  and  $s_2$  are the transmitted symbols over 2 Time slots leading to achieve a code rate of 1. Here \* indicates complex conjugate. These symbols are generated using a QAM constellation.  $a$ ,  $b$ ,  $c$  and  $d$  are complex valued-design parameters to be defined later.

Let us consider the same constraints of Proposition 1 with regard to the equivalent channel and the channel coefficients.

By substitution, equation (7) can be rewritten as follows:

$$Y = \sum_{k=1}^K \sqrt{\frac{\rho}{2}} \hat{H}_k \hat{X}_k + n_k \tag{15}$$

where  $\hat{H}_k = \begin{pmatrix} ah_{k1} & -ch_{k1} & bh_{k2} & -dh_{k2} \\ ch_{k2} & ah_{k2} & dh_{k1} & bh_{k1} \end{pmatrix}$  and

$$\hat{X}_k = [s_1 \quad s_2 \quad s_1^* \quad s_2^*]^T.$$

The complex valued design parameters are chosen such that to minimize the Euclidean distance  $D(s_1, s_2)$ ,

$$\begin{aligned}
 D(s_1, s_2) = & \sum_{k=1}^{N_r} \left| y_{k1} - h_{k1}(as_1 - cs_2) - h_{k2}(bs_1^* - ds_2^*) \right|^2 \\
 & + \sum_{l=1}^{N_r} \left| y_{l2} - h_{l1}(ds_1^* + bs_2^*) - h_{l2}(cs_1 + as_2) \right|^2
 \end{aligned} \tag{16}$$

By expanding  $D(s_1, s_2)$ , equation (7) can be rewritten as follow:

$$\begin{aligned}
 D(s_1, s_2) = & C + x(s_1, s_2) + \\
 & \sum_{k=1}^{N_r} 2\Re\{h_{k1}h_{k2}^*(ab^*|s_1|^2 - cb^*s_2s_1 - ad^*s_1s_2 + cd^*|s_2|^2)\} + \\
 & \sum_{l=1}^{N_r} 2\Re\{h_{l1}h_{l2}^*(dc^*|s_1|^2 + da^*s_1^*s_2^* + bc^*s_2^*s_1^* + ba^*|s_2|^2)\}
 \end{aligned} \tag{17}$$

where  $C$  is a constant independent of the symbols and  $x(s_1, s_2)$  is a function of the symbol pair  $(s_1, s_2)$ . To minimize the Euclidean distance, the following parameter pair have been used.

$$\begin{aligned}
 a = & \frac{(1-\sqrt{7}) + i(1+\sqrt{7})}{4\sqrt{2}} \\
 d = & 1 + i\sqrt{7} \\
 b = c = & \frac{1}{\sqrt{2}}
 \end{aligned} \tag{18}$$

**Proposition 3:** The corresponding space-time code is designed as follows, i.e.

$$X_k = \begin{pmatrix} as_1 - cs_2 & -ds_2^* + bs_1^* \\ -bs_2^* - ds_1^* & cs_1 + as_2 \end{pmatrix} \tag{19}$$

where  $s_1$  and  $s_2$  are the transmitted symbols over 2 Time slots leading to achieve a code rate of 1 [23]. Here \* indicates complex conjugate. These symbols are generated using a QAM constellation. a, b, c and d are complex valued-design parameters to be defined later.

Under the same conditions, equation (7) can be rewritten as follows:

$$Y = \sum_{k=1}^K \sqrt{\frac{\rho}{2}} \mathcal{H}_k^c \mathcal{X}_k^c + n_k \tag{20}$$

where  $\mathcal{H}_k^c = \begin{pmatrix} ah_{k1} & -ch_{k1} & bh_{k2} & -dh_{k2} \\ ch_{k2} & ah_{k2} & dh_{k1} & bh_{k1} \end{pmatrix}$  and

$$\mathcal{X}_k^c = \begin{bmatrix} s_1 & s_2 & -s_2^* & s_1^* \end{bmatrix}^T.$$

Based on the designed space time code, the designed parameters are chosen to minimize the Euclidean distance such that

$$\begin{aligned} a &= d = \frac{1}{\sqrt{2}} \\ b &= (1 - \sqrt{7}) + \frac{i(1 + \sqrt{7})}{4\sqrt{2}} \\ c &= \frac{1 + i\sqrt{7}}{4} \end{aligned} \quad (21)$$

Furthermore, at the receiver side which is the master node (MN), a near optimal-low complexity Minimum Mean Square Error (MMSE) and Zero Forcing (ZF) detectors are designed for decoding the received signal in order to achieve the optimal performance.

Denote

$$\begin{aligned} \mathbf{H} &= (\mathbf{H}_1^t, \mathbf{H}_2^t, \mathbf{L}, \mathbf{H}_k^t) \\ \mathbf{X} &= (\mathbf{X}_1^t, \mathbf{X}_2^t, \mathbf{L}, \mathbf{X}_k^t)^t \end{aligned}$$

Equation (7) can be rewritten as

$$\mathbf{Y}^t = \sqrt{\frac{\rho}{2}} \mathbf{H} \mathbf{X}^t + n \quad (22)$$

Let's denote

$$\mathbf{G}_{ZF} = (\mathbf{H}^H \mathbf{H})^{-1} \mathbf{H}^H \quad (23)$$

$$\mathbf{G}_{MMSE} = (2\mathbf{I} / \rho + \mathbf{H}^H \mathbf{H})^{-1} \mathbf{H}^H \quad (24)$$

$\mathbf{G}_{ZF}$  and  $\mathbf{G}_{MMSE}$  are the matrices of ZF decoder and MMSE decoder, respectively. The received signal can be estimated by

$$\bar{\mathbf{X}} = \mathbf{G}_{MMSE} \mathbf{Y}^t \quad (25)$$

where  $\bar{\mathbf{X}}$  is the estimated received symbols from the slave nodes.

#### 4. IMPLEMENTATION OF PSSS BASED CHANNEL STATE MEASUREMENT USING SDR

In order to investigate the performance of the proposed PSSS based channel state measurement in the real world, the complete PSSS channel estimate system is implemented on USRP X310. Two USRP X310 have been used as the transmitter and the receiver entities. The two USRP have been placed in a room designed perfectly for measurements to investigate the performance of the estimated channel and the overall system performance as shown in Figure 4.



Figure 4. PSSS based Channel Measurements.

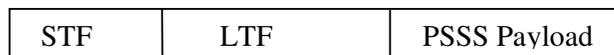


Figure 5. PSSS based channel estimation Frame Structure.

The frame structure is as shown in Figure 5. The short training field (STF) is basically used for detecting the presence of the signal and starting position of the transmitted frame based on delay and correlate algorithm. The delay and correlate algorithm is detailed discussed in [24]. The long training field (LTF) is used for channel estimation and equalization based on the proposed PSSS based scheme. The long training field is composed from 255 chips multiplied by 10 unique pilot symbols. The performance of the proposed scheme is shown in Figures 6-9.

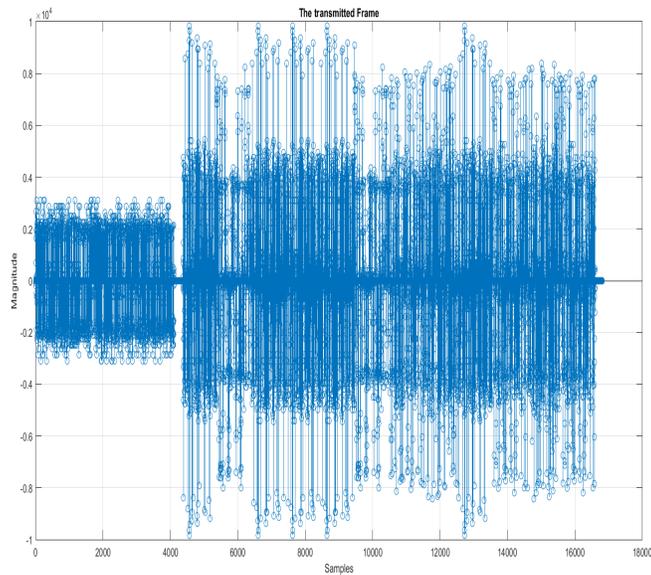


Figure 6. The transmitted PSSS Frame

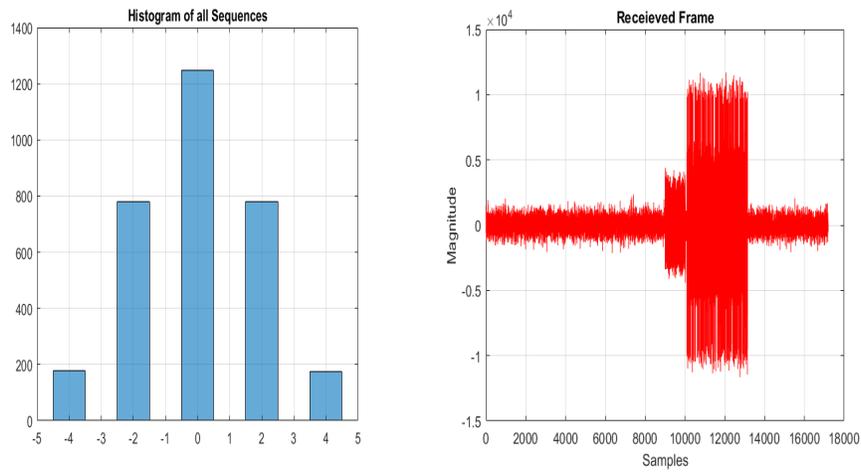


Figure 7. The histogram of the transmitted PSSS sequence and the received PSSS Frame.

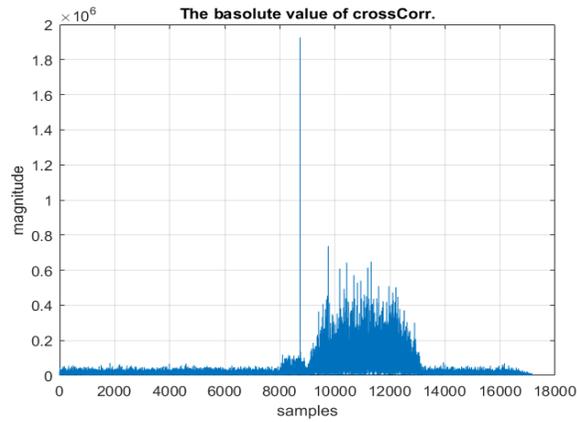


Figure 8. The result of the cyclic correlation.

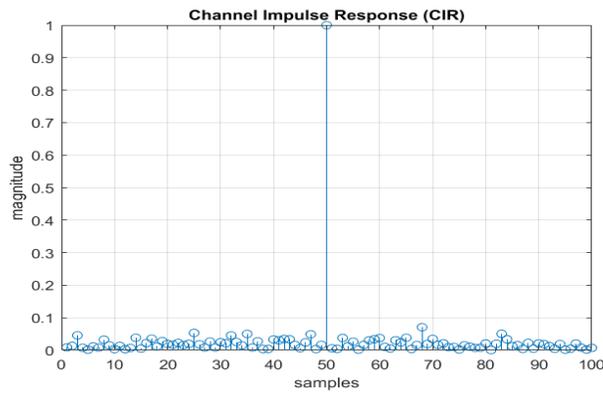


Figure 9. The measured channel impulse response.

It can be noticed from Figure 9 one realized channel between SN and MN. As Line of Sight is dominating, there is one strongest tap in the measured environment.

## 5. SIMULATION RESULTS

Figure 10 shows the proposed scenario using Quasi Deterministic Radio Channel Generator (Quadrige) channel model which follows a geometry-based stochastic channel modelling approach [25]. The parameters of the channel are specified stochastically, based on statistical distributions extracted from several real-time channel measurements. Therefore, more realistic results can be achieved by such scenario. The simulated geometry is as shown in the following figure.

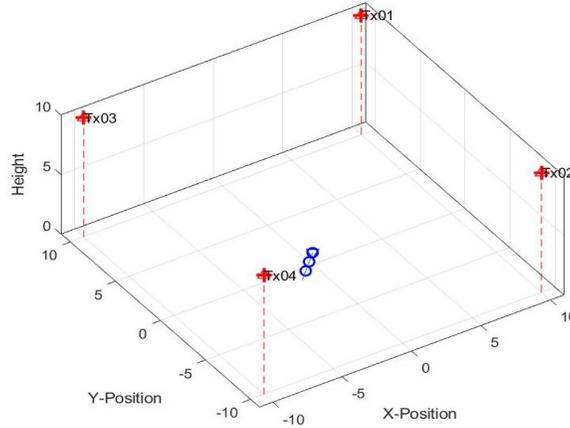


Figure 10. Proposed Scenario using Quadrige Channel Model

For the proposed system, the channel is represented by Quadrige channel model where the channel subjects to severe shadowing and pathloss for NLOS case. To compare the performance of the proposed codes, Alamouti Code has been selected as a reference for his wide adoption in many communication systems. As shown from Figure 11, the performance of the proposed space time codes outperforms Alamouti code for the case of two transmit antenna at the Slave Node (SN) and assuming only two distributed antennas at the Master Node (MN). It can be seen that the proposed designed code has a coding gain of 3 dB at  $BER=10^{-3}$  in comparison to Alamouti code, more specifically, for proposition 1 and proposition 3. It can be noticed that the performance of proposition 2 degrades at high SNR because of increasing the interference and LoS limitations with only 2 distributed antennas. However, the performance of proposition 1 and 3 was not affected so much because of the well-designed chosen parameters although the coding gain become less in comparison to Alamouti code but still surpasses it.

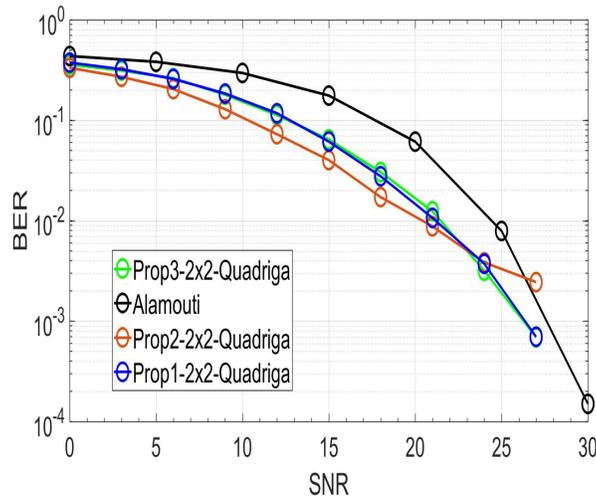


Figure 11. Comparison of the proposed codes and Alamouti code for 2x2 case using Quadriga Channel Model.

For the proposed Uplink scenario, where the MN has 4 distributed antennas over the factory hall, the achieved coding gain with the proposed space time codes is higher than Alamouti code. This attributes to the increasing number of received antennas at the MN which improves the overall performance to fulfill the reliability demands of Industry 4.0. In addition, this outstanding performance results from increasing the possibility of LoS communication. As shown from Figure 12, in such environment case, a high reliability can be achieved at low SNR with the combination of the proposed system configuration and the proposed designed codes. It can be noticed that Proposition 2 outperforms the other space time codes including Alamouti code under the same conditions of the environment. This attributed to the increasing possibility of LoS communication with the well-designed coding parameters to minimize the Euclidean Distance. It can be seen, for instance, at  $BER=10^{-4}$ , the proposition 2 has coding gain of about 5 dB compared to Alamouti code in such harsh channel conditions.

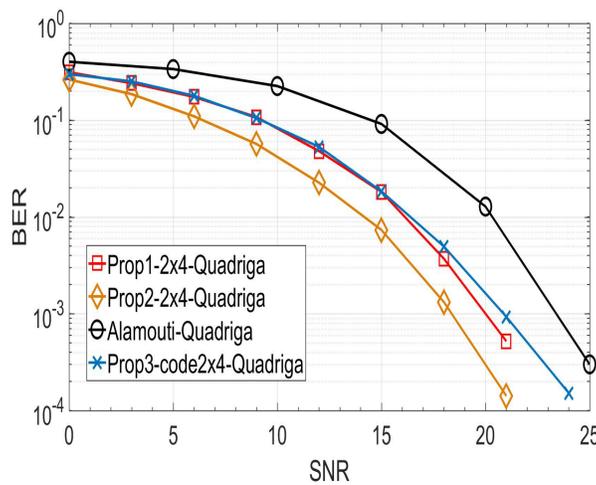


Figure 12. Comparison of the proposed codes and Alamouti code for 2 transmit antennas and 4 receive antennas case using Quadriga Channel Model.

## 6. CONCLUSION

In this paper, a set of space time codes are proposed for industrial automation. Mathematical framework has been developed to estimate the change in the phase of the channel. Practical implementation of PSSS based channel estimation using Software Defined Radio (SDR) has been presented for industrial communication and proved the efficiency of the proposed scheme in the real world. The proposed space time codes can achieve high coding gain leading to more robust communication to fulfil the reliability requirements in Industry 4.0 systems. The proposed codes are compared with Alamouti code and the simulation results proved that an outstanding performance can be achieved for the proposed codes in terms of BER. The proposed designed codes play an important role in standardization of Industry 4.0.

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