IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received December 21, 2019, accepted January 7, 2020, date of publication January 28, 2020, date of current version February 10, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2970108

ISI-Mitigating Channel Codes for Molecular Communication Via Diffusion

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This work was supported in part by the Scientific and Technical Research Council of Turkey (TUBITAK) under Grant 116E916, in part by the Ministry of Science and ICT (MSIT), South Korea, through the ICT Consilience Creative Program under Grant IITP-2017-2017-0-01015 supervised by the IITP, in part by the Basic Science Research Program through the National Research Foundation of Korea funded by the Ministry of Education under Grant NRF-2017R1A1A1A05001439, and in part by the State Planning Organization (DPT) of Turkey TETAM under Grant 2007K120610.

ABSTRACT One promising technique for communicating at the nanoscale is molecular communication (MC). In a molecular-communication-via-diffusion-scenario, the memory component of the channel is very high. This gives rise to what is known as inter-symbol interference. Traditional channel coding schemes cannot be utilized in MC due to the high memory. In this paper, a novel low complexity channel coding method is proposed for the molecular communication domain. The design of the proposed channel code takes into account the capability of a nano-device and the characteristics of the molecular communication channel. Simulation results confirm that the proposed method provides a significant improvement in terms of bit error rate. Moreover, a proof-of-concept implementation of the proposed coding scheme is done on a macro-scale testbed. The reliability of the communication link is shown to be significantly increased.

INDEX TERMS Molecular communications, nanonetworking, diffusion channel, channel coding.

I. INTRODUCTION

For most nanoscale applications, it is not a viable option to communicate via electromagnetic (EM) signal due to challenges included bio-compatibility, power, and possible health hazards. Nonetheless, molecular communication provides many desirable features, including bio-compatibility and nano-scale implementation. Nature uses a similar scheme and over billions of years has perfected it. Transferring the information via molecules can be done with through a variety of methods. Some of these are communication via micro-tubules [1], bacteria [2], calcium ions [3], or diffusion [4]–[7]. Due to its low energy consumption and simplicity, molecular communication via diffusion (MCvD) is one of the most preferred methods for carrying information between nano-machines [4]. Different features of the molecules can be used to encode the information. The most common features used to convey information are the type and the concentration of the molecules. [4], [8], [9].

In the most basic form of the MCvD, the transmitter releases molecules into the environment messenger molecules (MMs) for each symbol. When these released molecules enter the vicinity of the receptors, they are absorbed by the receiver. MMs have a probabilistic movement pattern that is subject to Brownian motion. Hence, some MMs take a more direct path towards the receiver and are absorbed within the communication interval while others follow a longer path and are absorbed later. This causes inter-symbol interference (ISI) and, if handled improperly, it can easily cause incorrect symbol detection [10], [11].

For a communication system, there is inevitably going to be some signal distortion that leads to incorrect detection. Increasing the power or decreasing the data rate are some of the techniques to improve the reliability of the communication. From a system designer's perspective, however, neither of these is desirable. By adding redundancy to the

The associate editor coordinating the review of this manuscript and approving it for publication was Zesong Fei.

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transmitted information, channel coding improves a communication link's reliability, but it also decreases the data rate. Redundant information is utilized at the receiver to recover the errors of the distorted signal. Researchers have proposed many different channel codes for numerous applications [12]. However, their effectiveness is significantly constrained by the heavy ISI effect. What is needed then is a new perspective.

In the literature, research on channel coding for molecular communications (MC) can be categorized into two groups. Considering well-known channel codes and designing new ones. For the first group, error-detection schemes are analyzed for MC in [13]. The authors in [14] studied the coding gain of Hamming codes, obtaining the optimal coding rate. The authors also analyzed energy consumption at the encoder and the decoder. The authors in [15] considered a more complicated coding scheme Reed-Solomon (RS) codes. The authors showed that RS codes could achieve higher coding gains, though implementing them is more complex than that of Hamming codes. In [16], [17] RS codes were also studied for a large-scale MC system. As expected, the bit error rate (BER) performance was better than the uncoded case. In [18], Euclidean geometry low-density parity check (EG-LDPC) and cyclic Reed-Muller (C-RM) codes were studied for MCvD. The authors compared the two codes' BER performances and also calculated their energy consumption. Minimum energy channel (MEC) codes were introduced in [19] for wireless nanosensor networks. And in [20], MEC codes were considered for the diffusive channel. The authors showed that a reduction in average energy consumption for per bit and an improvement in the BER performance over the Hamming codes. The authors in [21] considered self-orthogonal convolutional codes (SOCC) for MC, showing their coding gain is higher than the Hamming codes.

In the literature, some previous work has focused on designing new channel codes. The authors in [22] showed that Hamming distance is not the optimal metric for MCvD and introduce a new distance metric called molecular coding distance (MoCo). Similar work has been carried out by the author of [23]. In this study, a new distance metric called asymmetric-distance is proposed, and it is shown that this metric outperforms the Hamming distance when used for the decoding of convolutional codes. The authors also showed that their coding gain can be increased by re-defining according to this distance metric, the decoding region of Hamming codes. In [24], the authors considered transition probability for each codeword to another; they also introduce several heuristics and a mixed integer programming model to produce codebooks that are minimizing the transition probabilities is introduced. In this work, it was shown that the designed codebooks achieve, for high data rates, a considerably low BER performance. The drawback to this work is that it requires two types of molecules.

The authors in [25], [26] introduced ISI-free codes, which aim to completely eliminate the ISI between codewords completely with a low decoding complexity. At first glance, the idea seems very useful; upon close inspection however, the ISI-free codes are for cases where the data rate is very low. Crossover-resistant coding with time gap was introduced for MCvD in [27]; yet it is also considered for a very low data rate. The authors in [28] compared BER performance of ISI-free codes, MoCo codes, RM codes, and distinct Hamming codes for mobile robots equipped with molecular communication transceivers that release and detect alcohol (or any similar chemical) molecules.

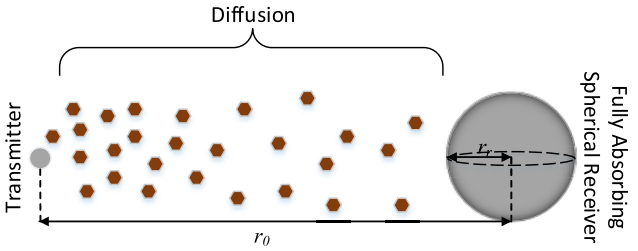


FIGURE 1. MCvD system model.

In this paper, we design a new channel code family considering the characteristics of the molecular communication channel. Compared to the other code families in the literature, our proposed code family has higher coding gain, even for high data rates. Furthermore, our code family is applicable for all different kinds of diffusive molecular communication channels without the requirement of the knowledge of the channel state information. This property is an important asset, as it leads to work for time-varying channels, a realm not extensively considered in the literature. This paper is organized as follows: In Section II, we define the system model used in the paper. Section III presents the code construction rules, decoding algorithm and adaptive threshold decoding mechanism for the corresponding code family. Section IV successful performance of the proposed code family; this is carried out by comparing it with other elegant code methods in the literature using both computer simulations and real time testbed experiments. Finally, Section V concludes the paper.

II. SYSTEM MODEL

A. MCVD CHANNEL

The proposed code family works for different kinds of channels, for demonstration purpose a channel with a point transmitter and a fully absorbing spherical receiver are assumed to be fixed in a three-dimensional fluidic environment and, as shown in Fig.1, to be communicating with each other via MCvD.

One of the most basic forms of MCvD is given in Fig. 1. Here the transmitter releases a number of MMs at the beginning of a symbol duration t_s and waits until the next transmission. Please note that the molecules diffuse randomly while they are following a movement pattern according to Brownian motion [29]. This operation is repeated for every symbol with a period of symbol duration at the transmitter side. At the receiver, MMs are absorbed and counted along with the symbol durations. At the end of the symbol duration,

the counter is reset and the receiver restarts counting. The absorption probability of a released MM until time t is

$$F_{hit}(t) = \frac{r_r}{r_0}\text{erfc}\left(\frac{r_0 - r_r}{\sqrt{4Dt}}\right), \quad (1)$$

where D is the diffusion coefficient, r_0 is the distance between the point transmitter and the center of the receiver, r_r is the radius of the receiver, and erfc$(\cdot)$ is the complementary error function [30]. Assume that the time is divided into evenly placed slots, and each slot's period is considered as symbol slot. After a molecule is released, the probability of absorption at a symbol slot is defined as channel coefficients. These are given as

$$p_k = F_{hit}(kt_s) - F_{hit}((k-1)t_s), \quad k = 1, 2, \ldots, I, \quad (2)$$

where I is the channel memory. Please note that p_1 corresponds to the probability that a molecule is absorbed by the receiver in its current symbol slot, while the remaining channel coefficients correspond to the probability that the released molecules are absorbed after the symbol slot in which it was released and was intended for. Following the assumption typically made in the literature, we assume that the channel coefficients are in descending order (i.e. $p_1 > p_2 ... > p_I$)[1] In a realistic communication scenario, numerous symbols should be transmitted consecutively. For this case, let $N_{i,k}^{Rx}$ denote the number of molecules that are released at the k-th symbol slot and received at i-th symbol slot, which is distributed according to a binomial distribution. The receiver number of molecules at the end of the i-th symbol can be stated as

$$N_i^{Rx} = \sum_{k=1}^{i} N_{i,k}^{Rx}. \quad (3)$$

For $M > 50$, the binomial distributed $N_{i,k}^{Rx}$ can be approximated by a normal distribution [31]. With normal distribution approximation, N_i^{Rx} can be stated as

$$N_i^{Rx} \sim \mathcal{N}\left(\sum_{k=1}^{i} M_k p_{i-k+1}, \sum_{k=1}^{i} M_k p_{i-k+1}\,(1 - p_{i-k+1}) + \sigma_n^2\right), \quad (4)$$

where σ_n^2 is the variance of the distribution of the counting (or environmental) noise which is assumed to be additive white Gaussian noise (AWGN), and M_k is the number of emitted molecules at the start of k-th symbol slot. Equations (2) and (1) show that the only parameter that affects the channel coefficients is the symbol duration. As t_s increases, p_1 also increases, which means ISI decreases, as also does the date rate.

To modulate the information, we use the quantity of the molecules, a type of modulation known as concentration shift keying (CSK). In this work, we use binary CSK (BCSK); this is for simplicity and because it is widely used in the literature [32]–[35]. Although the proposed method works for any binary CSK, without loss of generality and for the sake of simplicity, we chose on-off keying for modulation, which releases M molecules for bit-1 at the beginning of the symbol duration and does not release any molecules to send bit-0. At the receiver, if the number of the absorbed molecules in a symbol slot exceeds a pre-determined threshold, bit-1 is detected; otherwise, bit-0 is detected.

[1]This assumption holds when t_s is chosen large enough.

III. ISI-MITIGATING CODE

Our proposed code family, named after ISI-mitigating codes, is denoted as (n, k) ISI-mtg. This code family does not involve any consecutive bit-1s and uses an adaptive threshold, which is updated for each codeword. In particular, each codeword (CW) in the codebook has three properties:

- it cannot have consecutive bit-1s
- it starts with bit-0 to avoid consecutive bit-1s between two neighbors CWs
- it has to have at least one bit-1

The first and second properties are chosen to reduce the effects of ISI. In particular, in the literature, it is observed that consecutive bit-1s have an adverse effect on decoding of the subsequent bit-0s [36], [10]. Furthermore, another observation is that transmitting sparse sequences (hence fewer molecules) yields less ISI and better performances [37], [38]. Therefore, we aim to avoid having consecutive bit-1s by proposing the first and second properties. In addition to this, as will be seen in Section III-C, these properties also help the detection and correction of the observed signal. The third property is also used for the detection, especially for the proposed detection algorithm. In particular, we are going to propose an adaptive threshold based detection scheme. This scheme will be based on determining the maximum and minimum observations in the sequences, which belong to bit-1 and bit-0 positions, respectively, with high probability. Please note that the proposed code family is a block code where k-bit information sequences are mapped to n-bit CWs.

The optimum threshold for a CW is the threshold that minimizes the bit error rate after decoding. The proposed detection has been done with a threshold that adapts itself for each codeword. Let $\mathbf{r}^i = (r_2^i, r_3^i, ...r_n^i)$ be the received number of molecules of each bit of the i-th transmitted codeword, except for the first bit (r_1^i corresponds to bit-0, certainly). Since a codeword consists of bit-1s and bit-0s, the optimum threshold has to be between $d_1 = \max \mathbf{r}^i$ and $d_0 = \min \mathbf{r}^i$. By using this trivial observation, the threshold for the i-th codeword can be estimated as

$$\tau^i = ad_0 + (1-a)d_1, \quad (5)$$

where a is the scaling factor. With the correct selection of a, the optimum threshold can be found. Nonetheless, determining a is a challenging task.

The following section explains the construction of a codebook for a desired n. We then demonstrate how the erroneously detected binary sequences are corrected and mapped back to a codeword. Finally, two methods are introduced to determine the scaling factor a.

A. ISI ANALYSIS

The motivation behind our proposed coding scheme is constructing codes that leads to less ISI compared to the general transmission scheme. In order to show the advantage of the proposed properties, it is possible to compare the expected ISI terms for our method and the general transmission scheme. For a general transmission scheme, since there are no constraints, the expected ISI term for bit-1 and bit-0 can be easily obtained as

$$E\left[ISI_0^*\right] = E\left[ISI_1^*\right] = \frac{1}{2}\sum_{i=2}^{I} p_i, \tag{6}$$

where the superscript * is used to represent the equally likely transmission method. For our proposed method, since the transmission of bit-0s and bit-1s are not equally likely, we need to consider the all possible sequences (s^j) that may have been transmitted before a bit-0 or bit-1 symbol at m-th instant in order to evaluate the expected ISI terms. For example, the expected ISI for bit-0 can be calculated as

$$E\left[ISI_0\right] = \frac{1}{K_0}\sum_{j=1}^{K_0}\sum_{i=2}^{I} p_i s^j_{m-i+1} \tag{7}$$

where K_0 is the number of all possible sequences transmitted before bit-0. Similarly, we can write the corresponding expected ISI term for bit-1 as

$$E\left[ISI_1\right] = \frac{1}{K_1}\sum_{j=1}^{K_1}\sum_{i=2}^{I} p_i s^j_{m-i+1}. \tag{8}$$

Considering our coding design rules, for any given I, we can obtain the corresponding $E\left[ISI_0\right]$ and $E\left[ISI_1\right]$ values which would be less than $E\left[ISI_0^*\right]$ and $E\left[ISI_1^*\right]$ respectively. For instance, for $I = 5$, $E[ISI_0] = 0.42p_2 + 0.28p_3 + 0.28p_4 + 0.42p_5$, $E[ISI_1] = 0.4p_3 + 0.2p_4 + 0.4p_5$, and for $I = 10$, the ISI terms would be $E[ISI_0] = 0.38p_2 + 0.23p_3 + 0.29p_4 + 0.27p_5 + 0.28p_6 + 0.27p_7 + 0.29p_8 + 0.24p_9 + 0.38p_{10}$, $E[ISI_1] = 0.38p_3 + 0.23p_4 + 0.29p_5 + 0.27p_6 + 0.27p_7 + 0.29p_8 + 0.23p_9 + 0.38p_{10}$. Clearly, all the p_i terms have a multiplier smaller than 0.5. For a better understanding, the numerical values of expected ISI terms for $t_s = 200$ ms, $r_r = 5$ um, $d = 10$ um and $D = 79.4$ um^2/s are given in Fig. 2. As shown in the figure, the expected ISI is significantly lower than the uncoded case.

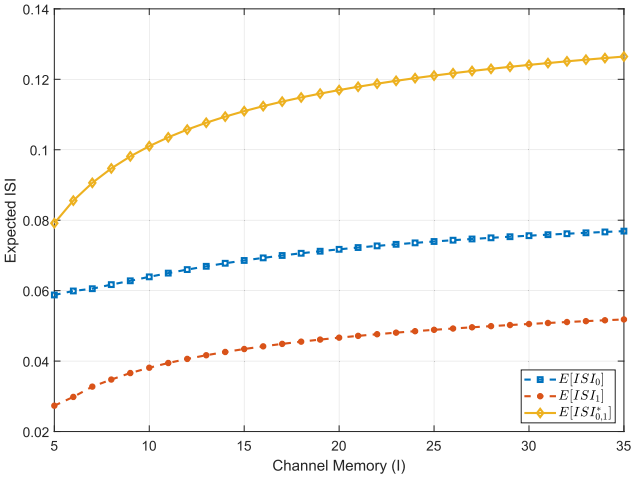


FIGURE 2. Expected ISI values of the uncoded and proposed method.

B. CODEBOOK CONSTRUCTION

A codebook with a desired length n can be constructed by following a set of simple steps. First, we need the set of codewords that satisfy the properties of the proposed code family. For $n = 3$, the set of codewords is

$$\mathbf{CW}_3 = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}, \tag{9}$$

where each row is a codeword. Note that the first column of $\mathbf{CW}_3$ is filled with zeros, since the first bit of each codeword has to be a bit-0. Let $\mathbf{W}_3$ be the matrix that contains bit sequences that start with bit-1 and do not have consecutive bit-1s for $n = 3$. The $\mathbf{W}_3$ can be stated as

$$\mathbf{W}_3 = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 0 & 1 \end{bmatrix}. \tag{10}$$

By concatenating $\mathbf{CW}_3$ and $\mathbf{W}_3$, $\mathbf{CW}_4$ can be constructed as

$$\mathbf{CW}_4 = \left[\begin{array}{c|ccc} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ \hline 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 \end{array}\right] = \left[\begin{array}{c|cc} \mathbf{0} & \multicolumn{2}{c}{\multirow{2}{*}{$\mathbf{CW}_3$}} \\ \mathbf{0} & & \\ \hline \multicolumn{3}{c}{\multirow{2}{*}{$\mathbf{W}_3$}} \end{array}\right], \tag{11}$$

In a similar manner, $\mathbf{W}_4$ can be constructed as follows:

$$\mathbf{W}_4 = \left[\begin{array}{c|ccc} 1 & 0 & 0 & 0 \\ \hline 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 \end{array}\right] = \left[\begin{array}{c|cc} 1 & \multicolumn{2}{c}{\mathbf{0}} \\ \hline \mathbf{1} & \multicolumn{2}{c}{\mathbf{CW}_3} \end{array}\right]. \tag{12}$$

In other words, for $n > 3$, with the knowledge of $\mathbf{CW}_n$ and $\mathbf{W}_n$, $\mathbf{CW}_{n+1}$ and $\mathbf{W}_{n+1}$ can be constructed as

$$\mathbf{CW}_{n+1} = \left[\begin{array}{c|cc} \mathbf{0} & \multicolumn{2}{c}{\multirow{2}{*}{$\mathbf{CW}_n$}} \\ \mathbf{0} & & \\ \hline \multicolumn{3}{c}{\multirow{2}{*}{$\mathbf{W}_n$}} \end{array}\right], \tag{13}$$

$$\mathbf{W}_{n+1} = \left[\begin{array}{c|cc} 1 & \multicolumn{2}{c}{\mathbf{0}} \\ \hline \mathbf{1} & \multicolumn{2}{c}{\mathbf{CW}_n} \end{array}\right]. \tag{14}$$

Starting from $n = 3$, the codebook for $n > 3$ can be constructed recursively, using equations in (13) and (14).

C. DETECTION AND ERROR CORRECTION

Due to the properties of the proposed coding scheme, we know that there are at least one bit-1 and one bit-0 present in the codeword. Moreover, the first bit of a codeword is definitely bit-0. By using these facts, the decoding algorithm for (n,k) ISI-mtg codes is given in Algorithm 1.

The decoding algorithm is mostly straightforward and simple. The part that needs further explanation is the last step. When two consecutive bits are detected as bit-1, at least one of them should be bit-0. Hence, there are three possibilities: 00, 01 and 10. To determine which one is the most probable,

we need to consider the effects of previously transmitted bits, which can be stated for the i-th bit by using (4) as

$$S_{i,y} \sim \mathcal{N}\left(\sum_{k=1}^{i-1} M_k p_{i-k+y+1}, \sum_{k=1}^{i-1} M_k p_{i-k+y+1}\left(1-p_{i-k+y+1}\right)\right), \tag{15}$$

where the subscript y stands for the delayed slot compared to i. The probabilities of detecting both z_v^i and z_{v+1}^i for any $v = 2, 3, .., n-1$ as bit-1 are stated in (16) where $s = n(i-1)+v$, and cw_v^i stand for the i-th codeword's v-th bit.

It is clear that (16c), as shown at the bottom of the next page, is the least likely one, as the probability of error is assumed to be higher than the probability of correct transmission. Comparing (16a) and (16b), as shown at the bottom of the next page, is unfortunately no trivial task and calls for more observations. To begin with, analyzing both the correct and erroneous transmission probabilities are very challenging. Instead, we focus on the terms that stand for the error probability. The error terms at (16a) and (16b) are $P(N^{Rx}_{s+1,s} + S_{s,1} > \tau^i)$ and $P(S_{s,0} > \tau^i)$, respectively. Assume that the channel coefficients after term p_4 are neglected. Then, possible binary sequences that has been transmitted are: (0010), (1010), (1001), (1000) and (0101).[2] Now we are looking for the most possible transmitted sequence when (x011) is detected where x could be bit-0 or bit-1. First (0101) and (1000) are very unlikely since the probability of detecting an error is much lower than the probability of detecting a bit correctly. For these sequences to be detected, two errors should be done while for others there is only one bit error. When the third bit is detected erroneously, which is the case for (1001), the channel coefficients that causes the error are p_3. Finally, for (0010) and (1010), the last bit is detected erroneously and the channel coefficients that cause it p_2 and $p_2 + p_4$ respectively. Since p_2 is greater than p_3 correcting two consecutive bit-1s as (10) is in general a feasible solution. Please note that the result would be same even when coefficients greater than p_4 are not neglected. The exact same steps can be followed for higher order coefficients and it can be shown that (10) is the best choice here. Another important aspect is since we only consider the error terms, this is not the maximum likelihood (ML) solution for this problem. The ML solution is not preferred since it increases the complexity of this operation gradually.

Thus, the probability calculated by (16a) is higher in general, and when two consecutive bit-1s are detected, the last bit is corrected as bit-0.

When three consecutive bit-1s are detected, there are five different combinations that might have been transmitted: 101, 100, 010, 001, and 000. Since the error probability is much lower than the probability of correct transmission, 101 is the most probable sequence. While the other combinations have at least 2-bit errors, 101 has a single bit error. This result is consistent with the two consecutive bit-1s problem. When 111 is detected, the first two consecutive bit-1s are resolved by setting the second bit as 0 and the result becomes 101, which is the same result when two consecutive bit-1s are corrected as 10.

Even though it's very unlikely, it is possible to have four, five or more consecutive bit-1s at the detection stage. As explained, the most likely transmitted sequence can be found by correcting 11 -> 10. Starting from the beginning, correcting the 11 as 10 is a consistent correction method for any number of consecutive bit-1s. For example, for five consecutive bit-1s 11111, the most likely solution is (10101) which can be found by first correcting the first two bit-1s and found 10111 and then by correcting the third and fourth bit-1s which yields the most likely solution 10101. This method of correction can be applied to any number of consecutive bit-1s.

D. THRESHOLD SCALING CONSTANT ESTIMATION

The optimum threshold for each codeword varies between the minimum and the maximum R^i values as indicated in (5). In fact, a very challenging task consists of estimating the optimum a for every codeword. To determine a, we propose two methods.

The first method is by using pilot codewords (coded pilot symbols). Since the pilot codewords are also known at the receiver, the threshold that corresponds to the least amount of errors, which is also referred as the optimum threshold, for each codeword can be found. Note that there might be multiple threshold values that minimize the detection error. In these cases, we select the optimum threshold as the median of these thresholds. If L number of pilot codewords are transmitted, the equation to find the optimum threshold for each of them can be stated as

$$a d_0^i + (1-a) d_1^i = \tau_{opt}^i, \tag{17}$$

where $i = 1, 2, \ldots, L$. This equation can also be written as

$$(d_0^i - d_1^i) a = \tau_{opt}^i - d_1^i. \tag{18}$$

This equation set can be stated in matrix form as

$$\begin{bmatrix} d_0^1 - d_1^1 \\ d_0^2 - d_1^2 \\ \vdots \\ d_0^L - d_1^L \end{bmatrix} [a] = \begin{bmatrix} \tau_{opt}^1 - d_1^1 \\ \tau_{opt}^2 - d_1^2 \\ \vdots \\ \tau_{opt}^L - d_1^L \end{bmatrix}. \tag{19}$$

Because there is only one variable, which is a, and there are L equations, a unique solution does not exist, but least square (LS) solution can be found as

$$a_{LS} = (\mathbf{d}^T \mathbf{d})^{-1} \mathbf{d}^T (\tau_{opt} - \mathbf{d}_1), \tag{20}$$

where $\mathbf{d} = [d_0^1 - d_1^1, d_0^2 - d_1^2, \ldots, d_0^L - d_1^L]^T$ and $\tau_{opt} = [\tau_{opt}^1, \tau_{opt}^2, \ldots, \tau_{opt}^L]^T$. Please note that the pilot symbols are sent once to determine a at the beginning of the communication.

[2] (0001) is also an option but this sequence cannot be detected as (x011). That's why it is not included in this analysis.

Algorithm 1 Proposed Decoding Algorithm

let $\mathbf{z}^i = (z_2^i, \ldots, z_n^i)$ be the binary indicator of i-th received binary sequence
let $l = 2, 3, \ldots, n$
$z_l^i \gtrless \tau^i$ ▷ make a decision on z_l^i for all l
$mp = \arg\max \mathbf{r}^i$. ▷ find the bit position with the highest number of molecules
$z_{mp}^i = 1$ ▷ mp is the most likely position that bit-1 is sent
$z_{mp-1}^i \leftarrow 0, z_{mp+1}^i \leftarrow 0$ ▷ consecutive bit-1s are not allowed
if $z_l^i = 1$ and $z_{l+1}^i = 1$ **then**
    $z_{l+1}^i \leftarrow 0$ ▷ this part is explained in (15)-(16)
end if

To determine a using the second method, we propose an analytic solution. This method does not need the transmission of any pilot symbols, which results in a gain in the rate compared to the first method. This gain is particularly meaningful when a small number of symbols is going to be transmitted. Moreover, the scaling constant may be updated when the receiver has the knowledge of the channel coefficients. This feature is useful when the channel varies fast. Please note that for a slowly varying channel, due to the overall adaptive threshold structure, both methods can be used efficiently without updating the constant. The downside of this method is the need for channel coefficients and its complexity. As explained in the previous section, after the thresholding, we correct 11 as 10. In other words, an erroneously detected bit-0 that comes after a bit-1 is most likely corrected. That's why, the possible strongest ISI term that causes an error on bit-0 may come from the two previous bits, which is distributed as $ISI_3 \sim \mathcal{N}(M_3p_3, M_3p_3(1-p_3))$ (instead of ISI_2). The scenario we are trying to avoid here is transmitting $x0100$ and detecting $x0101$ as it cannot be corrected at the decoding stage. Please note that ISI terms on bit-1s are not destructive. In contrast, they help the symbol to be detected as bit-1. Assume that the distribution of the molecules if bit-1 is transmitted at the current slot, which can be modeled as $X_{signal} \sim \mathcal{N}(M_1p_1, M_1p_1(1-p_1))$. Obviously, the number of received molecules at x-th slot can be represented as $N_x^0 = \sum_{x=3}^{\infty} b_x ISI_x$ if the transmitted symbol is bit-0, and $N_x^1 = X_{signal} + \sum_{x=3}^{\infty} b_x ISI_x$ if the transmitted symbol is bit-1. Our approach for deriving an analytic threshold consists of determining the weakest N_x^1 and the strongest N_x^0 that form the most susceptible case for erroneous decoding. For this case, we derive the probability of error and minimize this function with respect to the threshold. In particular, ISI_x for $x > 3$ is ignored, number of received molecules at i-th slot for transmitting bit-0 and bit-1 are $N_x^1 = X_{signal}$ and $N_x^0 = ISI_3$ respectively. The error probability for decoding N_x can be written as

$$P_E = P_0 Q\left(\frac{\tau^i - Mp_3}{\sqrt{Mp_3(1-p_3)}}\right) + P_1\left(1 - Q\left(\frac{\tau^i - Mp_1}{\sqrt{Mp_1(1-p_1)}}\right)\right), \quad (21)$$

where P_0 and P_1 are the transmission probability of bit-0 and bit-1, respectively. By replacing τ^i with (5), taking the derivative and equating it to 0 yields. Finally, the solution of (22) and (23), as shown at the bottom of the this page, can be obtained as, where $U = \frac{Mp_1(1-p_1)}{P_1}$ and $R = \frac{Mp_3(1-p_3)}{P_0}$.

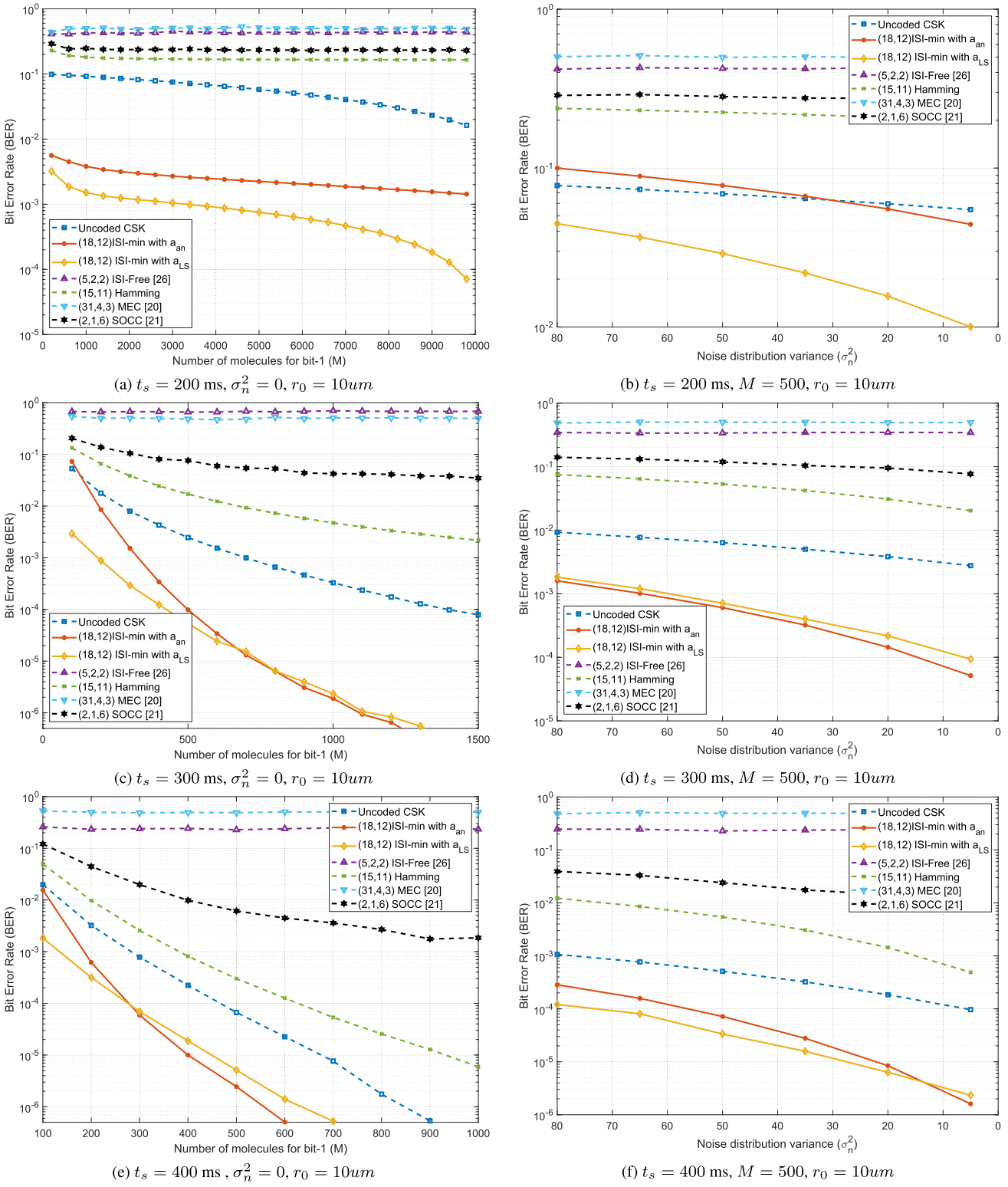
$$P(z_v^i = 1, z_{v+1}^i = 1 | cw_v^i = 1, cw_{v+1}^i = 0) = P(N_{s,s}^{Rx} + S_{s,0} > \tau^i) P(N_{s+1,v}^{Rx} + S_{s,1} > \tau^i), \quad (16a)$$

$$P(z_v^i = 1, z_{v+1}^i = 1 | cw_v^i = 0, cw_{v+1}^i = 1) = P(S_{s,0} > \tau^i) P(N_{s+1,s+1}^{Rx} + S_{s,1} > \tau^i), \quad (16b)$$

$$P(z_v^i = 1, z_{v+1}^i = 1 | cw_v^i = 0, cw_{v+1}^i = 0) = P(S_{s,0} > \tau^i) P(S_{s,1} > \tau^i). \quad (16c)$$

$$P_1 \frac{e^{\frac{-(-Mp_1 + ad_0 + (1-a)d_1)^2}{2Mp_1(1-p_1)}}}{\sqrt{Mp_1(1-p_1)}} = P_0 \frac{e^{\frac{-(-Mp_3 + ad_0 + (1-a)d_1)^2}{2Mp_3(1-p_3)}}}{\sqrt{2Mp_3(1-p_3)}}. \quad (22)$$

$$a_{an} = \frac{Mp_1R - Mp_3U + d_1U - d_0R - \sqrt{R \quad U(Mp_1 - Mp_3)^2 - 2RU \log\sqrt{\frac{U}{R}}(R-U)}}{(U-R)(d_1 - d_0)}. \quad (23)$$



(a) $t_s = 200$ ms, $\sigma_n^2 = 0$, $r_0 = 10um$

(b) $t_s = 200$ ms, $M = 500$, $r_0 = 10um$

(c) $t_s = 300$ ms, $\sigma_n^2 = 0$, $r_0 = 10um$

(d) $t_s = 300$ ms, $M = 500$, $r_0 = 10um$

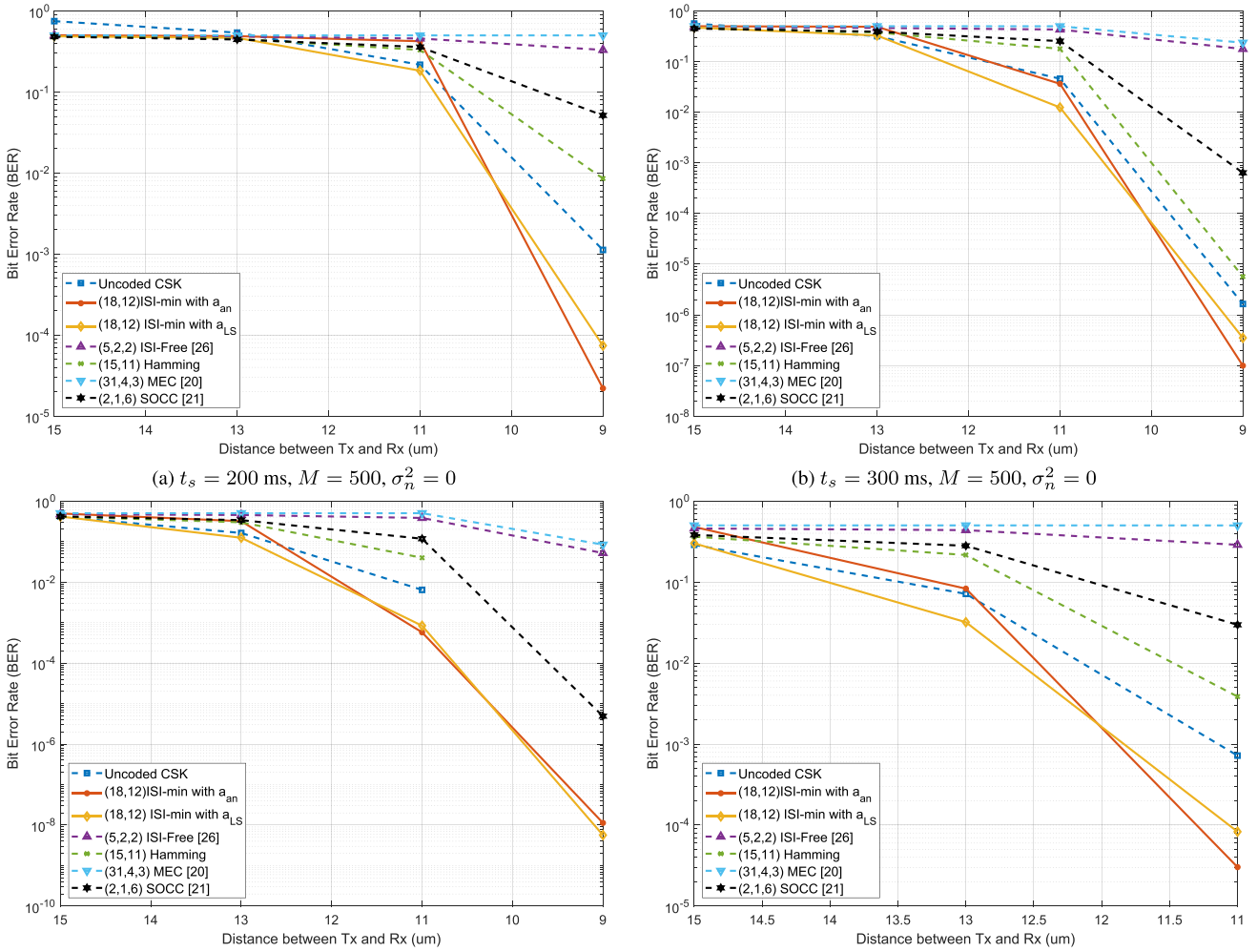
(e) $t_s = 400$ ms , $\sigma_n^2 = 0$, $r_0 = 10um$

(f) $t_s = 400$ ms, $M = 500$, $r_0 = 10um$

FIGURE 3. Comparison of different coding strategies and uncoded transmissions for different symbol durations, transmitted number of molecules, and the variance of the noise distribution.

Please note that while the LS solution determines the value of a once and uses it for subsequent transmissions, the analytic solution is updated a for every codeword.

As a final note, the ISI for a bit-0, can be upper bounded with $\sum_{i=2}^{\lfloor (I-1)/2 \rfloor} ISI_{2i-1}$. For classical coding techniques (or coding techniques that are not specifically tailored



(a) $t_s = 200$ ms, $M = 500$, $\sigma_n^2 = 0$

(b) $t_s = 300$ ms, $M = 500$, $\sigma_n^2 = 0$

(c) $t_s = 400$ ms, $M = 500$, $\sigma_n^2 = 0$

(d) $t_s = 500$ ms, $M = 500$, $\sigma_n^2 = 0$

FIGURE 4. **Comparison of different coding strategies and uncoded transmissions for different symbol durations, and Tx-Rx distance.**

for MCvD), this kind of an upper bound would be higher (in general $\sum_{i=2}^{I} ISI_i$). Although, this upper bound does not have a one-to-one relation with error rate; we still believe that it is nice to have it to show the superior side of the proposed coding technique.

IV. SIMULATION AND EXPERIMENTAL RESULTS

A. SIMULATION RESULTS

While comparing coding strategies, it is very important to normalize the average power and symbol duration according to the coding rate. We use the uncoded communication data rate and average power as a reference and normalize accordingly. For an (n, k) block code, the symbol duration t_s and the number of molecules released for bit-1 M are decreased to $\frac{k}{n}t_s$ and $\frac{k}{n}M$, respectively.[3] Decreasing the power and the symbol duration affects the BER performance significantly. Thus, channel coding strategies should perform at least better than the uncoded case under normalized condition. Otherwise, it is not meaningful to use that channel coding strategy at all.

In general, channel coding strategies are based on correcting up to a number of errors in an erroneously detected binary sequence. If the received sequence has more errors than the channel code can correct, then the received sequence cannot be decoded correctly. As a result, classical channel codes perform better when the error rate is low, and have a worse BER performance than the uncoded communication otherwise. However, such a coding strategy is not suitable for MCvD due to the heavy ISI channel. Our proposed coding scheme also does not follow such a traditional strategy; hence, it is possible to have a desirable performance even when the channel conditions are harsh. The simulation parameters for the uncoded case are given in Table 1[4]

[3]Please note that when sparse codes are used, M would change according to k, and the total number of bit-1s and bit-0s in the codebook.

[4]The values in this table have been widely used in the literature. As given in [10], they are typical to simulate an environment where human insulin hormone is used as the messenger molecules, and a device whose capabilities are similar to a pancreatic β-cell is used as the transmitter.

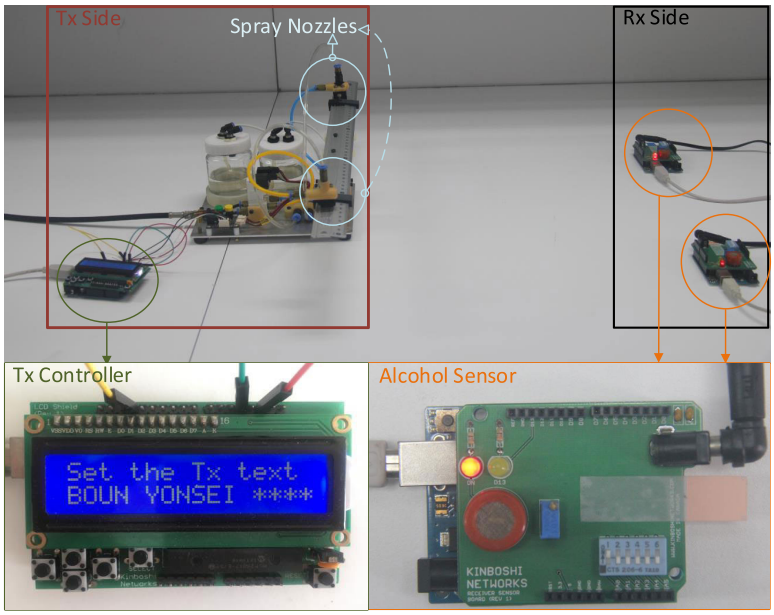


FIGURE 5. Testbed structure.

TABLE 1. Simulation Parameters.

Parameter	Variable	Value
Diffusion Coefficient	D	79.4 um^2/s
Receiver Radius	r_r	5 um
Tx-Rx Distance	r_0	10 um
Channel Memory	I	100
Symbol Duration	t_s	200 - 500 ms
Released MM (per bit-1)	M	$400 - 10000$
Message and Block Length	(n, k)	$(18, 12)$

Please note that while a pre-determined threshold is needed in the BCSK, our proposed scheme has an adaptive threshold. Thus, a pre-determined threshold is needed for comparison. The BER performance of other coding strategies and the uncoded case are obtained according to a threshold that minimizes the bit error rate at the receiver (this is also called the genie threshold).

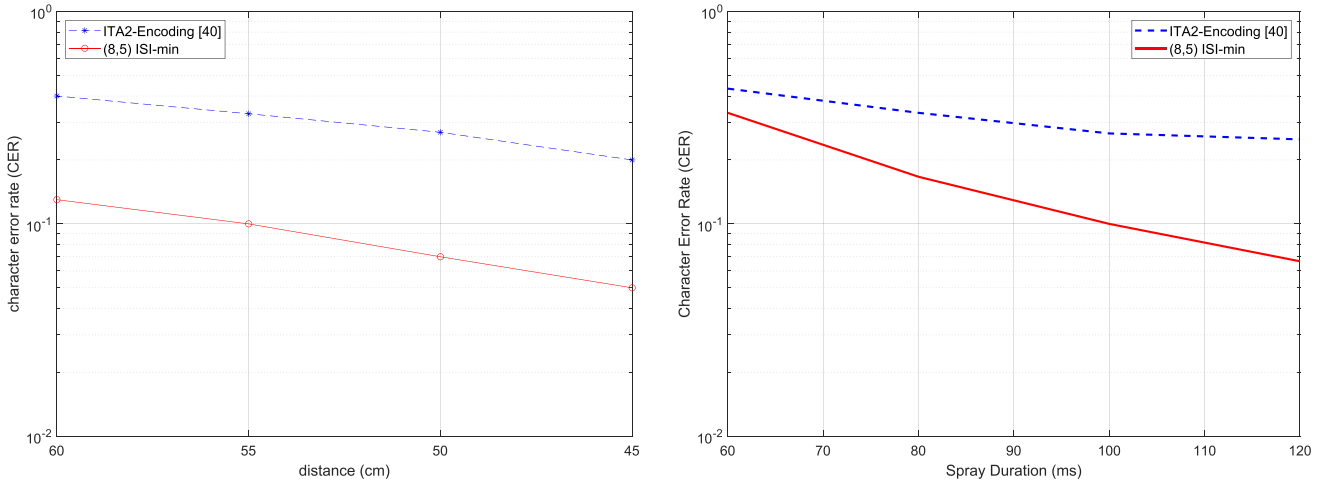
The simulation results for the uncoded BCSK, (15,11) Hamming codes, (31,4) MEC codes [19], [20], (5,2,2) ISI-free codes [25], [26], (2,1,6) SOCC codes [21], and the proposed (18,12) ISI-mtg coding scheme with pilot symbol aided and analytically determined thresholds for different conditions are given in Fig. 3. and Fig. 4.

The first observation about the results is that the analytical solution has a desirable BER performance for high symbol durations, yet the same is not correct for low symbol durations. This is expected since the analytical solution is based on the assumptions that hold for high symbol durations. On the other hand, the pilot symbol aided method performs well, independent of the symbol duration. The results when noise is present are also given in Fig. 3, where the coding gain is significantly high for both analytic and pilot aided method. Please note that the proposed pilot symbol aided coding scheme has a better performance than the analytic solution in general; however, the need for pilot symbols at the start of the communication might be a challenge for this method. Fortunately, the pilot symbols should be transmitted only once at the start of the communication. It is important to realize that the analytical solution has a desirable performance for low symbol durations, and has a similar (or better) performance for high symbol durations without having any pilot symbols at the start.

The second observation is that our coding scheme has a clear advantage over other coding schemes, and our scheme performs better than the uncoded case even for low symbol durations, like $t_s = 200$ ms. A more important result is that at low symbol durations and high transmitted number of molecules, while the other coding techniques cannot benefit from high power, due to their error floor, our scheme does not reach an error floor. In other words, a fast data rate communication with a considerably low probability of error is possible at high power with the proposed schemes.

B. EXPERIMENTAL RESULTS ON A MACRO-SCALE MIMO TESTBED

To verify our proposed coding and detection scheme, we conduct real-time experiments by implementing the proposed scheme on the macro scale testbed presented in [39]. The system mainly consists of a transmitter part and a receiver part. At the transmitter part, a microcontroller controls the two spray nozzles separately, and at the receiver side, two alcohol sensors are driven by two separate micro-controllers. Please note that the coding at the transmitter and the detection at the receiver are also handled by these micro-controllers.



(a) Spray duration = $120ms$ (b) Tx-Rx Distance = $50cm$

FIGURE 6. CER performances of the proposed scheme and the ITA-2 encoding scheme [39].

While transmitting a bit sequence, it is evenly divided into two-bit sequences that are sent in parallel channels by the two spray nozzles and detected in parallel by alcohol detectors. The components of the testbed are shown in Fig. 5.

In [39], International Telegraph Alphabet No. 2 (ITA-2) is used to represent 26 different characters with five bits. Moreover, the authors propose three different detection algorithms: adaptive thresholding, practical zero forcing, and genie-aided zero-forcing. While genie-aided zero-forcing performs best, it is not practical as its name indicates. Authors show that the other the two detection algorithms perform almost the same. Hence, the adaptive algorithm is used with ITA-2 for comparison.

In our system, we use eight bits to represent 26 different characters. For eight bits, there are 33 different binary sequences that obey the rules of the proposed coding scheme. We choose 26 codewords that have less number of bit-1s. For detection, we send 100 pilot symbols and use LS solution to determine the threshold scaling constant a. Please note that the constant a is only determined once at the beginning of the communication. Due to the change in the temperature and the flow in time, channel conditions are slowly varying. However, the results show that updating the constant a is not necessary as explained in the previous section. Symbol duration $t_s = 4000$ ms is chosen for our system, and the average power and data rate are normalized as explained in Section IV-A. Since counting the number of released molecules is not possible in the testbed, we use spray duration to adjust the power. Character error rates (CER) for different spray durations, and distances between the transmitter and the receiver, r_0, are given in Fig. 6, and the results show that our scheme has a clear advantage in terms of CER.

V. CONCLUSION

In this paper, a channel coding scheme and a detection technique that is specifically tailored for this coding scheme are proposed. First, without having consecutive bit-1s, a new codebook is introduced. For detection purposes, the codebook consists of codewords that have at least one bit-1. After that, the steps to correct the received vectors are proposed so that the erroneously detected bits are corrected. Finally, a new detection algorithm, which takes advantage of the information of the maximum and the minimum number of received molecules for bits of every transmitted codeword is proposed. The results show that the proposed scheme has a significant improvement in terms of bit error rate. Finally, the proposed scheme is implemented on a macro-scale testbed to show its practical use and improvement in the character error rate.

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