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Mobile Molecular Communications: Positional-Distance Codes

Song Qiu[1], Taufiq Asyhari[2], Weisi Guo[1*]

***Abstract*—Molecular communications between mobile nano-robots will likely yield bit transposition errors. In such a scenario, it is important to design and test a new family of appropriate forward-error-correction codes. In this paper, we first construct a proof-of-concept robot to demonstrate how transposition errors arise. We then review state-of-the-art research in positional-distance codes and implement such codes onto the robot to achieve reliable mobile molecular communications. In order to imitate a large number of transposition errors, we model the mobile molecular communication channel as a double random walk channel. The results show that the positional-distance codes can achieve a superior performance over classical Hamming-distance codes and the performance is not sensitive to the initial starting position of the robots.**

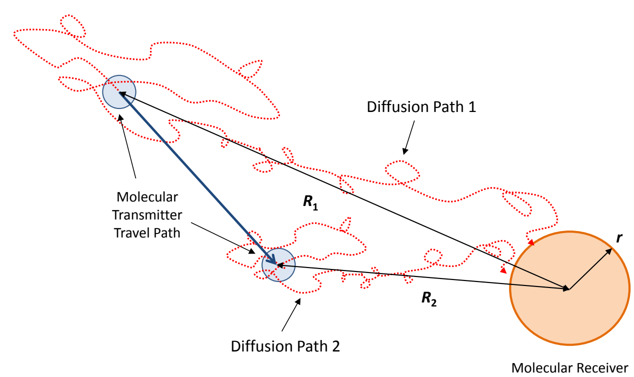

Fig. 1. Illustration of mobile molecular communications with a transmitter moving towards the receiver.

I. Introduction

Being able to communicate at the nano-scale can unlock new areas of engineering. In particular, by enabling nano-robots to communicate with each other, potential application areas such as nano-medicine and nano-sensing can be realized. In such environments, traditional notions of wave antenna design and propagation falter due to the small antenna size and transmit energy restrictions, as well as the complex propagation channels involved (i.e., viscous body fluids with biological obstacles). Inspired by biological communications, conveying data using molecules has served as an inspiration for telecommunication engineers [1]. In recent years, a number of physical layer and signal processing advances have been made in molecular communications via diffusion (MCvD) [2], [3]. Despite the fact that MCvD is likely to take place between mobile nano-robots or -machines [4], mobile molecular communications has received relatively little attention at the physical layer level.

The main contribution of this paper is to show that in a mobile molecular communications system, the movement of the transceivers are likely to cause bits to be disordered due to the slow propagation rate relative to the transceivers' movement speed. Therefore, traditional forward-error-correction (FEC) codes are inadequate in dealing with the transposition errors. Building on a recent review of FEC codes [3], a range of FEC codes are evaluated in the presence of transposition errors. In Section II, we first review the MCvD channel and noise model, as well as existing coding strategies. In Section III, we demonstrate how transposition errors can realistically arise in a mobile molecular system, built with a mobile robot and a proven existing molecular communication testbed [5]. In Sections IV and V, we examine how positional-distance code design can achieve a superior performance compared to traditional Hamming-distance approaches, and how it can be implemented on the robotic platform by providing the pseudo-code for encoding and decoding.

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II. Review of Channel & Coding Strategies

MCvD channels are based on classical Random Walk (RW) and Brownian motion models. An illustration of the channel is given in Figure 1. The generic received signal pulse can be said to be $y = \phi x + n$, where the channel gain is ϕ, input is x, and the additive noise is n. The channel gain ϕ is:

$$\phi(R,t) = \frac{r}{r+R}\frac{R}{(4\pi D t^3)^{1/2}}\exp\left(-\frac{R^2}{4Dt}\right), \quad (1)$$

where R is the transmit distance, D is the diffusivity, t is time, and r is the radius of the receiver. This assumes that each molecule that falls within the radius of the receiver is permanently absorbed and converted into a signal output for detection. The detector is commonly designed to detect the peak response or a change in gradient at the peak response, which occurs at the following time and corresponding value [3]:

$$t_{\max} = \frac{R^2}{6D}, \quad \phi_{\max} \propto \frac{Dr}{R^2(R+r)}. \quad (2)$$

In terms of the additive noise n, one form of noise is known as *counting noise*, which arises from the random arrival of independent and identically distributed (i.i.d.) molecules [3]. For n emitted molecules, the number of molecules arriving at the receiver is Binomial distributed $\sim \mathcal{B}(n,\phi)$. Given that the number of molecules per pulse (n) is large and the first passage probability ϕ is neither close to 1 nor 0, the binomial

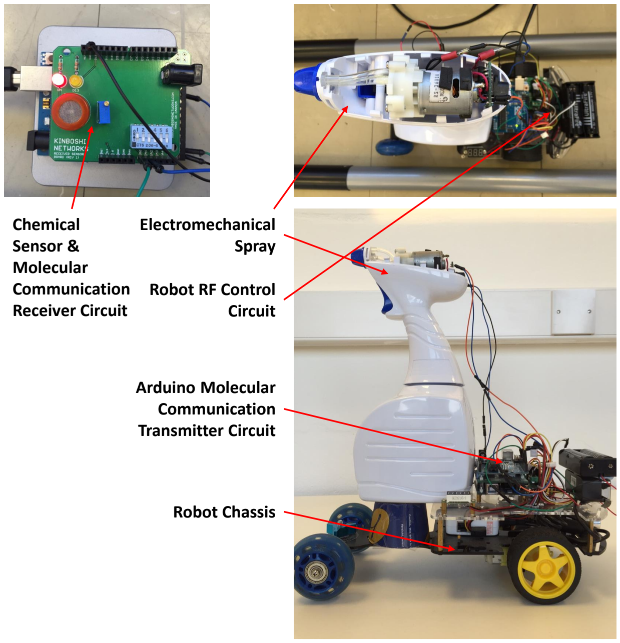

Fig. 2. The robotic molecular communication system mounted on a chassis.

distribution can be approximated to a normal or Gaussian distribution $\sim \mathcal{N}(n\phi, n\phi(1-\phi))$.

FEC coding is an important aspect of modern digital communications. In classical code design, one is concerned with decoding errors due to additive noise. A usual criterion of designing good codes is the *Hamming distance* of the code. It is widely known that Hamming distance is related to the error detection and correction capability of the code. If the code has a Hamming distance of d, it can correct up to $\lfloor (d-1)/2 \rfloor$ bit errors. Relatively simple block codes use added parity check bits to enable the correction of errors, i.e., Hamming codes are described as $n = 2^m - 1$ length codes, where m is the number of parity check bits. A comparison of Euclidean geometry low density parity check (EG-LDPC) and cyclic Reed-Muller (C-RM) codes can be found in [6].

III. Mobile Molecular Channel

Traditionally, bit transposition errors have been produced by examining the arrival time of a single molecule (see inverse-Gaussian (IG) channel modeling [7]). However, in a real system, each symbol or bit is likely to be represented by a large quantity of molecules (i.e., there are 6×10^{23} molecules in 1 gram of hydrogen). Therefore, the arrival time averaged across all the molecules is unlikely to vary significantly unless either the channel varies or the transceivers move.

A. Mobile Molecular Channel

When one considers a mobile molecular channel, the distance R component in Eq. (1) will vary in accordance to time. In the most extreme scenario, the transmitter will be travelling towards the receiver at a velocity that is significantly faster than the rate of diffusion. In this paper, we assume that the movement of the transmitter does not in itself disrupt the

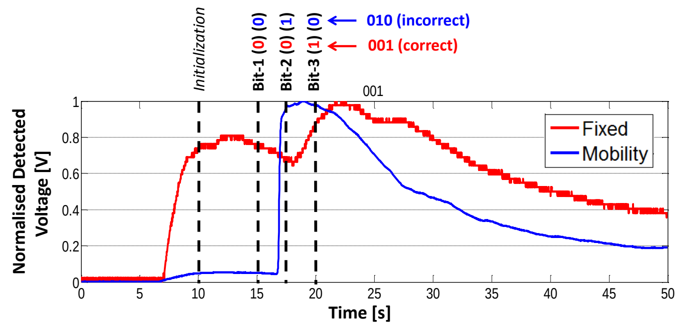

Fig. 3. Plot of experimental pulse response from 1 trigger symbol and 3 sequential transmitted symbols. The transmitter transmits 001. Each of the time markers show the receiver sampling points. Each bit received is decoded for the (fixed - red) (mobile - blue) channels.

diffusion process. As shown in Figure 1, consider 2 symbols transmitted sequentially at distances R_1 and R_2 at times t_1 and t_2 respectively (symbol period of $T = t_2 - t_1$). Assume that the detector uses the received pulse response's peak for detection. For each transmitted pulse, the time to peak value $t_{\max}$ given in Eq. (2), will differ such that the second symbol will arrive at a time ΔT after the first:

$$\Delta T = T + \frac{R_2^2 - R_1^2}{6D}. \tag{3}$$

For equal distant transmissions, the time difference will simply be the symbol period T. Referring to Eq.(3), in order for bit transposition errors not to occur ($\Delta T > 0$), the following must hold true: $T > \frac{R_1^2 - R_2^2}{6D}$. Certainly, as a simple observation, if the symbol period is larger than the peak response arrival time ($T > \frac{R_1^2}{6D}$), then bit transposition errors cannot occur. However, two caveats exist with adapting the dynamic symbol period in this manner: 1) every subsequent symbol will need to wait a dynamic time period based on the current transmission distance estimated (difficult to achieve), and 2) the resulting data rate can be extremely variable and low. Hence, there is a need to implement new code designs to combat bit transposition errors.

B. Experimental Setup: Mobile Robots

In order to model the effects of mobility on bit errors, we have built a mobile molecular communication system. The system is mounted on a radio-frequency (RF) remote controlled chassis, which can move towards and away from the receiver. A photo of the transmitter and receiver molecular communication circuits can be found in Figure 2. An Arduino control circuit is used to perform the digital signal processing (DSP) elements at the transmitter and receiver sides, and the full implementation is in the original paper [5].

To demonstrate how bit transposition occurs, the robot first remains static and sends an initialization pulse to signal to the receiver that it is ready. After waiting for 5s, the robot then begins moving towards the receiver and sends 3 symbols at a fixed interval of 2.5s. A non-coherent gradient detector (i.e., difference detector [8]) is used to improve robustness against channel variations. Referring to Figure 3, 001 is transmitted. For the static case (red), the initialization pulse is received followed by a decrease in gradient at the Bit-1 and Bit-2, indicating a 0 bit for both. This is then followed by an increase in gradient, indicating that Bit-3 is a 1. Hence the data of 001 is correctly received. However, in the mobile case (blue), the receiver will receive a sharp increase in the Bit-2 position and no change in the Bit-1 and Bit-3 positions, indicating a 010. That is to say, the original Bit-3 has shifted to Bit-2, which is a transposition error. By implementing the $(4, 2, 1)$-ISI-free FEC code (see Algorithms 1 and 2 in Section IV), the robot was able to combat single transposition errors.

TABLE I
ASSIGNING CODEWORDS FOR THE (4,2,1) ISI-FREE CODE.

Message bits	Assignment if the previous codeword has	
	last bit '0'	last bit '1'
00	0000	1111
01	0001	1000
10	0011	1100
11	0111	1110

IV. Positional-Distance Code Design

Consider an (n, k)-block-coding strategy that maps k-bit message into n-bit codeword and is implemented in the mobile robot. The movement of the robot causes bit transposition where earlier bits can arrive later than more recent bits, and vice-versa. Therefore, when a stream of k-bit messages are encoded using this strategy, the mobile molecular channel may exchange the bits' positions within a codeword (*Intra-Codeword Errors*) and across codewords (*Inter-Codeword Interference*). Reference [3] has reviewed several block-coding techniques that are aimed to mitigate errors due to bit transposition. In the following, we discuss the rationales behind the development of those techniques and explore the suitability of the $(4, 2, 1)$-ISI-free code as the most superior code in [3, Sec. IV] for implementation in the mobile robot.

A. Intra-Codeword Errors

We first examine intra-codeword transposition errors that affect (n, k)-block codes to encode 2^k messages. For an n-bit block, the total number of words that can be generated is 2^n. As mentioned in Section II-B, existing block codes have largely been designed based on maximization of the Hamming distance from the chosen 2^k out of 2^n possible words. This maximization is intuitively useful to correct corrupted bits due to noise/distortion. However, it is likely to be ineffective when the errors are mainly due to permutation of bits' positions.

1) Back to Repetition Codes: In a trivial example, let us consider block length of $n = 2$ and two possible codebooks, both with the same Hamming distance of 2: $\mathcal{C}_1 = \{01, 10\}$ and $\mathcal{C}_2 = \{00, 11\}$. In the event of a bit transposition error, it is clearly preferable to use codebook $\mathcal{C}_2$. This demonstrates that Hamming distance alone may not be the only parameter to consider. Codebook $\mathcal{C}_2$ is precisely the repetition code for $n = 2$. Since the structure of a repetition code for any length $n > 0$ is well preserved in the event of bits transposition, the code is effective in combating intra-codeword errors. Yet, repetition codes only achieve a code rate of $R_{\text{Rep.}} = \frac{1}{n}$, whereby a large n will yield a very small coding rate.

2) Distinct Hamming Weight (DHW) Codes: From a different perspective, we can see that the codewords in the above repetition code $\mathcal{C}_2$ have the Hamming weights of 0 and 2, respectively. We can further observe that each of these Hamming weights remains unchanged under permutation of bits within a codeword. Building upon this observation, we can then construct a coding scheme in which each codeword can be identified from its Hamming weight. Such a coding scheme for a length-n block is referred to in [3] as a *distinct Hamming-weight (DHW) code* of length n. It is worth noting that the DHW code is not unique as the distinct Hamming-weight requirement can be satisfied by more than one set of codewords. A length-n DHW code can achieve the largest rate of:

$$R_{\text{DHW}} = \frac{1}{n} \log_2(n + 1), \tag{4}$$

which improves on repetition codes by a factor of $\log_2(n)$ for large codewords. A specific instance of length-4 DHW code is given in [3] as $\mathcal{C}_{\text{DHW}} = \{0000,\ 1000,\ 1100,\ 1110\}$.

B. Inter-Codeword Errors

In order to mitigate bit transposition (both within and across codewords), the authors in [9] introduced a new coding parameter, namely molecular coding (MoCo) distance, to replace Hamming distance for code design in molecular communications. Consider two possible binary codewords $\boldsymbol{c}_i$ and $\boldsymbol{c}_j$. Building upon on-off keying modulation with a single molecule for each entry of $\boldsymbol{c}_i$ and $\boldsymbol{c}_j$, the MoCo distance of $\boldsymbol{c}_i$ and $\boldsymbol{c}_j$ (with its variants for simplification) is defined by

$$d_{\text{MoCo}}(\boldsymbol{c}_i, \boldsymbol{c}_j) \triangleq -\log\left(\Pr\{\boldsymbol{c}_j|\boldsymbol{c}_i\}\right), \tag{5}$$

where $\Pr\{\boldsymbol{c}_j|\boldsymbol{c}_i\}$ is the channel transition probability from $\boldsymbol{c}_i$ to $\boldsymbol{c}_j$ that is governed by molecular diffusion. In parallel to Hamming distance approach, the best code is thus given by a codebook that maximizes the minimum pairwise MoCo distance. An example for $n = 4$ is provided in [9], i.e., $\mathcal{C}_{\text{MoCo}} = \{0000,\quad 1000,\quad 0010,\quad 1110\}$. It was argued that from the MoCo distance maximization and the guard band indicator of bit '0' at the end of each codeword in $\mathcal{C}_{\text{MoCo}}$, this coding construction addresses permutation of bits within each codeword and across codewords. This construction, however, has a significant drawback from the fact that we need to exhaustively search for the best code according to criterion in (5), and will be less suitable for practical implementation.

C. Implementation of Transposition Error Correction Code

The work in [10] recently developed a systematic step-by-step approach to construct a code that attempts to reduce bit transposition errors. The resulting code is denoted as (n, k, ℓ) ISI-free code where n and k follows from the usual coding notations of block length and message length, respectively, and an extra parameter ℓ is the transposition level that can be corrected. The name ISI-free is somewhat misleading, as the codeword does not target the removal of inter-symbol-interference (ISI), and rather it is a positive side effect. An

Algorithm 1 Encoding method using (4,2,1)-ISI-free code

Input: $\boldsymbol{d}$ (vector of N information bits), prev_bit (initialized to 0, indicating last bit of previous codeword)
Output: $\boldsymbol{c}$ (vector of coded bits: length $2N$)
Assume: All vectors start with index 1

if N is odd **then**
  $\boldsymbol{d} \leftarrow [\boldsymbol{d} \quad 0]$
  $N \leftarrow N+1$
end if
for i from 1 to $N/2$ **do**
  $\boldsymbol{m} \leftarrow \boldsymbol{d}[2i-1:2i]$
  if prev_bit == 0 **then**
    switch $\boldsymbol{m}$ **do**
      case $[0\,0]$
        $\boldsymbol{c}[4i-3:4i] \leftarrow [0\,0\,0\,0]$
      case $[0\,1]$
        $\boldsymbol{c}[4i-3:4i] \leftarrow [0\,0\,0\,1]$
      case $[1\,0]$
        $\boldsymbol{c}[4i-3:4i] \leftarrow [0\,0\,1\,1]$
      case $[1\,1]$
        $\boldsymbol{c}[4i-3:4i] \leftarrow [0\,1\,1\,1]$
  else
    switch $\boldsymbol{m}$ **do**
      case $[0\,0]$
        $\boldsymbol{c}[4i-3:4i] \leftarrow [1\,1\,1\,1]$
      case $[0\,1]$
        $\boldsymbol{c}[4i-3:4i] \leftarrow [1\,0\,0\,0]$
      case $[1\,0]$
        $\boldsymbol{c}[4i-3:4i] \leftarrow [1\,1\,0\,0]$
      case $[1\,1]$
        $\boldsymbol{c}[4i-3:4i] \leftarrow [1\,1\,1\,0]$
  end if
  prev_bit $\leftarrow \boldsymbol{c}[4i]$
end for
return $\boldsymbol{c}$

Algorithm 2 Decoding (4,2,1)-ISI-free codewords

Input: $\boldsymbol{r}$ (vector of N coded bits)
Output: $\boldsymbol{y}$ (vector of decoded bits: length $N/2$)
Assume: N is a multiple of 4, all vectors start with index 1

for i from 1 to $N/4$ **do**
  $\boldsymbol{w} \leftarrow \boldsymbol{r}[4i-3:4i]$
  $hw \leftarrow$ Hamming_Weight($\boldsymbol{w}$)
  switch hw **do**
    case 0
      $\boldsymbol{y}[2i-1:2i] \leftarrow [0\,0]$
    case 1
      $\boldsymbol{y}[2i-1:2i] \leftarrow [0\,1]$
    case 2
      $\boldsymbol{y}[2i-1:2i] \leftarrow [1\,0]$
    case 3
      $\boldsymbol{y}[2i-1:2i] \leftarrow [1\,1]$
    case 4
      $\boldsymbol{y}[2i-1:2i] \leftarrow [0\,0]$
end for
return $\boldsymbol{y}$

example of $(4,2,1)$ ISI-free code is illustrated in Table I. The ISI-free code partially uses Hamming weight features of that DHW code in order to minimize the transposition errors within a codeword. The bit transposition at level ℓ across codewords can be corrected by ensuring that for two consecutive codewords, the first ℓ bits of the latter are the same as the last ℓ bits of the former. In terms of implementation of the $(4,2,1)$-ISI-free FEC code in the mobile robot, the steps are presented in Algorithms 1 and 2, which include both the encoding and decoding techniques. These were used to both conduct experiments on the robot and generate BER performance results using Monte-Carlo simulations (see next section).

V. Performance Comparison

A. Double Random Walk Mobility Model

In order to create 10^3-10^5 bits with transposition possibilities, a robotic experiment would take an extremely long time, and furthermore, realistic physical boundary conditions will add bias to the results. In order to generate a sufficient number of bit transposition errors and apply a range of FEC codes, we employ a RW model for the molecular movement, whereby the distance between the transmitter and the receiver also follows a RW model. We call this a double RW (double-RW) model. We first consider the movement of the transmitter's location as a 1-dimensional Wiener process. Intuitively, the Wiener process is a continuous-time random process with independent Gaussian-distributed increments. We assume the process starts off at position $R(0)=L$, where L is the initial distance (also mean separation) distance between the transmitter and the receiver. Thereafter, the position $R(k)$ at discrete time k is a Gaussian random variable (r.v.) with distribution $R(k) \sim N\left(L, k\sigma^2\right)$. The variance parameter σ^2 is given by $\sigma^2 = 2D_{\text{Tx}}$ where D_{Tx} can be interpreted as the movement speed of the transmitter.

We now consider molecular channel coding using binary alphabets $\{0,1\}$ to construct the code of length n. Upon encoding a message m, the n-bit codeword $\boldsymbol{c}$ is modulated using a relevant sequence of molecules. For a bit-1 and bit-0, the transmitter emits one single molecule of two different molecule types respectively. Let the expected time of arrival be t_{max}, given in Eq. (2). Due to the random motion of the molecule, the random arrival time can be treated as $t_{\text{max}}+z$, where z is the time noise. The noise z is IG distributed [7]:

$$f(z) = \sqrt{\frac{\lambda}{2\pi z^3}} \exp\left(-\lambda \frac{(z-\mu)^2}{2\mu^2 z}\right), \quad z>0, \qquad (6)$$

where $\mu = R(k)/v$ and $\lambda = 2(R(k)/D)^2$. The drift velocity v is always towards the receiver. As mentioned earlier, the distance R is a Gaussian r.v. ($R(k) \sim N\left(L, k\sigma^2\right)$). By using the double RW model, we are able to simulate a large number of bit transposition errors to yield statistically significant comparative results for different FEC codes.

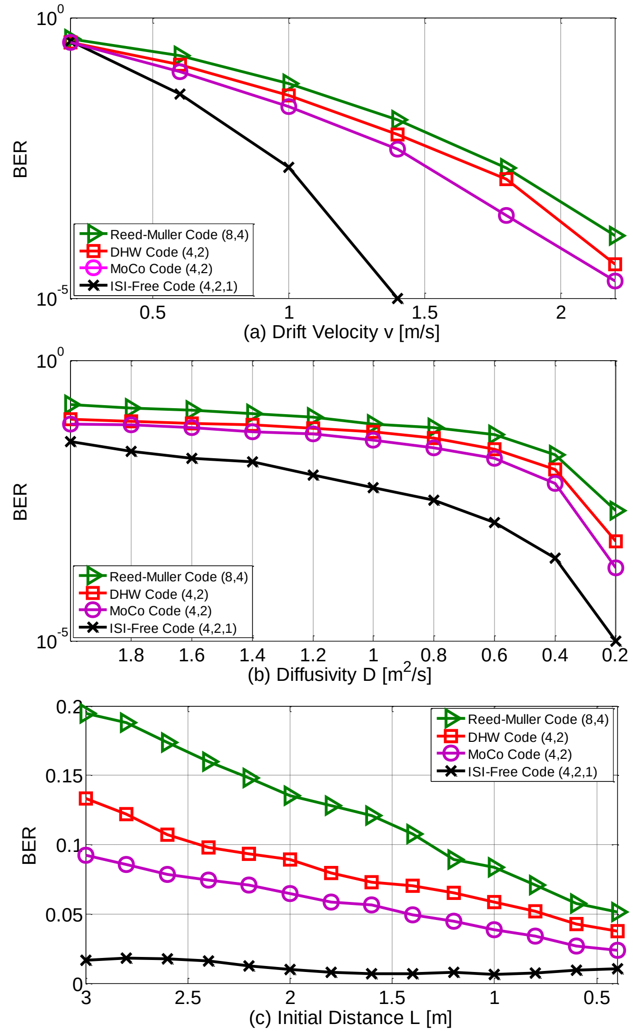

Fig. 4. BER of various coding schemes as a function of: (top) drift velocity v, (middle) molecular diffusivity D, (bottom) initial distance L. The static parameters used are: $D = 1m^2/s$, $L = 1m$, $D_{\text{Tx}} = 10^{-10} \times Dm^2/s$, and $v = 1m/s$. All the coding schemes have rate of 1/2.

B. Numerical Results

In Figure 4, we plot the bit-error rate (BER) of the various coding techniques in the presence of bit transposition errors introduced by the double RW model. From the three subfigures, we can see that the initial distance plays a minor role in the BER due to the resulting movement. We can also see that the (8,4) Reed-Muller code (design based on the Hamming distance) has the worst BER performance. It can also be clearly observed that the optimal (4,2) MoCo-distance code has a better performance than the DHW code due to the fact that the MoCo distance (5) closely resembles the actual channel transition probability as opposed to the Hamming weight criterion. On the other side of the coin, the main limitation of the MoCo-distance code is the difficulties to generate codewords without resorting a full-scale search to the possible combination of bits. From Figure 4, we can further identify that the (4,2,1) ISI-free code is superior to other coding techniques in terms of BER. The ability of always meeting the requirement of mitigating $\ell = 1$-level transposition errors and the availability of step-by-step coding mechanism make this code to be attractive for implementation in mobile molecular communications.

Perhaps, a critique to the construction of the (4,2,1) ISI-free code is the idea that two codewords are used to represent a single group of message bits as shown in Table I. This idea leads to the inefficiency in terms of coding rate. From this type of construction, it can be further shown that for a block length of n bits, rate beyond $\frac{n-1}{n}$ is unattainable. In fact, the example above with the (4,2,1) ISI-free code has rate only $\frac{1}{2}$ and increasing rates beyond $\frac{1}{2}$ is challenging. The work in [10] partly addressed this, but further improvement and works are still required to enhance the coding efficiency.

VI. Conclusions

Molecular communications between mobile nano-robots will yield bit transposition errors. In this paper, we first reviewed current FEC coding strategies designed at combating additive noise that result from molecule counting discrepancies. However, when mobile molecular communications is considered, a far more damaging source of noise is the transposition of bits. In such a scenario, it is important to design a new family of appropriate FEC codes. We have used mobile robots equipped with molecular communication transceivers to demonstrate how transposition errors arise. We then employ positional-distance codes and use simulation results to show a significant improvement over classical Hamming-distance coding strategies, and we show that the BER is not sensitive to the initial starting position of the robots. The positional-distance code is then implemented onto the robot to achieve reliable mobile molecular communications.

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