Modulation Techniques for Communication via Diffusion in Nanonetworks

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***Abstract*—Communication via diffusion of molecules is an effective method for transporting information in nanonetworks. In this paper, novel modulation techniques called Concentration Shift Keying (CSK) and Molecule Shift Keying (MoSK) are proposed for coding and decoding information of the so-called messenger molecule concentration waves in nanonetworks. The first technique, CSK, modulates the information via the variation in the concentration of the messenger molecules whereas MoSK utilizes different types of messenger molecules to represent the information. Using simulation, the performance of these modulation techniques is evaluated in terms of susceptibility to noise and transmission power requirements. The new techniques achieve high channel capacity values, in particular, the MoSK technique exhibits more robustness against noise and requires less power.**

***Index Terms*—nanonetworks, communication via diffusion, molecular communication, modulation techniques**

I. Introduction

Nanonetworking is a new communication paradigm that encompasses various communication methods that can be used to transmit information between micro- and/or nano-scale machines [1]. Molecular communication is envisioned as a promising method at this scale as an alternative to traditional approaches such as electromagnetic wave or acoustic wave based systems.

In molecular communication, the information is carried via so-called messenger molecules. Inspired by the cellular biological communication systems, different communication methods for molecular communication systems have been proposed in the literature [1]. These systems can be categorized by their effective ranges as short range, e.g., molecular motors [2]), short to medium range, e.g., ion signaling [3], communication via diffusion [4]), and long range molecular communication systems, e.g., bacterium based communication [5], pheromone signaling [6]).

Among these systems, we focus on short and medium range Communication via Diffusion (CvD) system in nanonetworks where the information is encoded over messenger molecule concentration waves. The transmitter emits messenger molecules based on the current part of the bit sequence. These molecules propagate through the environment following diffusion dynamics, and some are received by the receptors via the formation of chemical bonds at the receiver as shown in Figure 1. The formation of such a chemical bond triggers a series of events at the receiver, which results with the decoding of the transmitted information.

Several aspects of this communication system have already been studied in the literature. Different channel models have been developed and the channel capacity of this communication system has been evaluated using these models in [7], [8], and [9].

In this paper, we propose two new modulation techniques, Concentration Shift Keying (CSK) and Molecule Shift Keying (MoSK) for nanonetworks where communication is realized via diffusion (CvD system). These techniques can be used for short and medium range molecular nanonetworks in order to increase the communication efficiency and the bits per symbol rate. By simulations, we evaluate various performance aspects such as the effect of signal power and resistance to the noise affects, of the proposed modulation techniques in a single transmitter and single receiver environment.

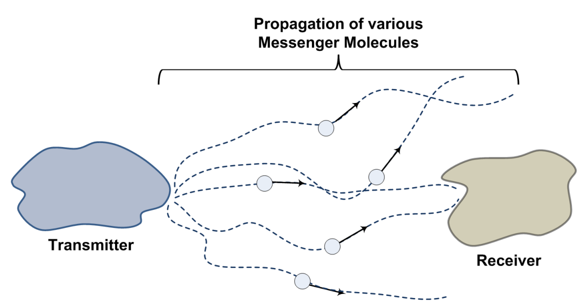

Figure 1. The communication model

The remainder of the paper is organized as follows. In Section II, we propose the new modulation techniques for nanonetworks with communication via diffusion. The channel model is explained in Section III. In Section IV, we present performance evaluation of these modulation techniques and conclude the paper with Section V.

II. Modulation Techniques

In nanonetworks with communication via diffusion (CvD system), the information is sent using a sequence of symbols spread over sequential time slots as one symbol in each slot. The symbol sent by the transmitter is called the "intended symbol" and the symbol received at the receiver is called the "received symbol." A variety of modulation techniques can be used for the mapping between messenger molecule reception and the received symbol, in other words, symbol detection. The symbol can be modulated over various "messenger molecule arrival properties" at the receiver, e.g., concentration, frequency, phase, molecule type, to form a signal.

We propose two modulation techniques, CSK and MoSK, based on the unique properties of this communication paradigm.

A. Concentration Shift Keying (CSK)

The concentration of the received messenger molecules is used as the amplitude of the signal. The receiver decodes the intended symbol as "1" if the number of messenger molecules arriving at the receiver during a time slot exceeds a threshold (τ), "0" otherwise. In order to represent different values in symbols, the transmitter releases different number of molecules for each value the symbol can represent: for "0" the transmitter releases n_0 molecules whereas for "1", n_1 molecules are released.

CSK is analogous to Amplitude Shift Keying (ASK) in classical communication. Instead of using two n values, e.g., n_0 and n_1, and a single threshold, the symbol can be tailored to represent b bits by using 2^b different values with $2^b - 1$ threshold levels.

We use the classical modulation naming convention based on the number of bits per symbol. CSK can be implemented in practice as BCSK (Binary CSK) or QCSK (Quadruple CSK), depending on the bits per symbol rate.

- If $b = 1$, CSK is called Binary CSK (BCSK)
- If $b = 2$, CSK is called Quadruple CSK (QCSK).

The CvD system using CSK technique can be affected adversely from Inter Symbol Interference (ISI) which can be caused by the surplus molecules from previous symbols. Due to the diffusion dynamics, some messenger molecules may arrive after their intended time slot. These molecules cause the receiver to decode the next intended symbol incorrectly.

It is shown in [10] that in the CvD system, only the last symbol has a significant ISI effect over the current symbol. The severity of this ISI related error depends on the selection of the threshold values and the number of thresholds used in the technique. With the increase in the number of bits per symbol, the error due to ISI also increases.

B. Molecule Shift Keying (MoSK)

MoSK utilizes the emission of different types of messenger molecules to represent information. For the transmission of n information bits in one symbol, 2^n different molecules are utilized, each representing a combination of the 2^n different n-bit sequences. The transmitter releases one of these molecules based on the current intended symbol. The receiver decodes the intended symbol based on the type and the concentration of the molecule received during a time slot. If the concentration of a single molecule type exceeds the threshold τ at the receiver, the symbol is decoded based on the bit sequence corresponding to this molecule type. On the other hand, an error is assumed, if the concentration of any molecule types does not exceed the threshold or the concentration of more than one molecule type exceeds the threshold.

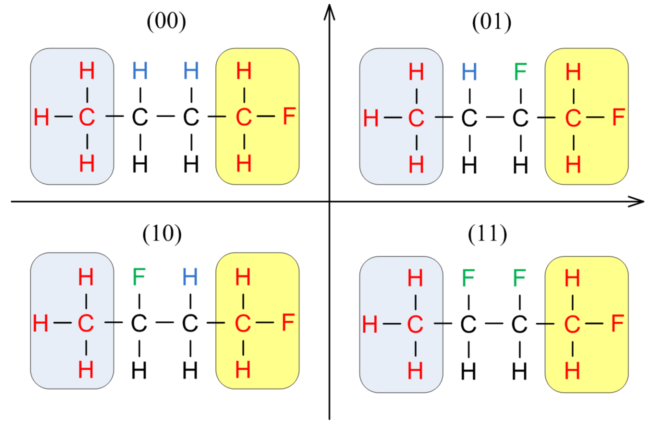

Figure 2. Constellation of QMoSK using Hydrofluorocarbon based messenger molecule

Inspired by [11], Hydrofluorocarbons can be used as the messenger molecule structure for systematically designing 2^n different molecules for n bit logical information representation. Based on the message to be transmitted, a special messenger molecule is synthesized using three parts: header, trailer, and the chemical bit element. A single header and a single trailer are present in each molecule representing the start and the end of the message. For each bit of information, a chemical bit element is synthesized. This chemical bit element has two forms: one for representing "0" and another one representing "1". All of these parts are linked to each other using chemical bonds to form a single messenger molecule. In Figure 2, we depict a 2-bit constellation realization of this modulation technique called Quadruple MoSK (QMoSK).

Similar to the CSK technique, the surplus molecules from the previous symbols also cause ISI when MoSK technique is used. However, MoSK is less susceptible to ISI effects than the CSK technique when the bits per symbol rate (b) is greater than 1. In this case, a single threshold is used for MoSK whereas b thresholds are required for CSK. However, this advantage of the MoSK technique comes at the cost of the requirement for complex molecular mechanisms at both the transmitter and the receiver for messenger synthesis and decoding purposes, respectively. Also, a corruption in such a messenger molecule may cause some or all of the information in the symbol to get lost. This information corruption may cause severe problems since a corruption may only change the bit sequence inside the messenger molecule and the resulting corrupted molecule may still represent some information albeit not the one sent by the transmitter. Without special mechanisms designed to detect (and/or correct) such errors, the receiver cannot distinguish a correct molecule from a corrupted one. In order to protect the messenger molecules from such environmental corruption, it can be sheathed inside a protective shield, e.g., vesicles, at the transmitter. When the receiver gets the vesicle, it extracts the messenger molecule inside and discards the vesicle. The design of an appropriate protective layer requires further research regarding its energy cost, protection value, and effect on diffusion dynamics.

III. Communication Channel Models

In order to evaluate the performance of different modulation techniques, we develop a channel model where we assume that the time is divided into equal sized slots (called symbol durations t_s) in which a single symbol can be sent. Since the molecules propagating through the environment exhibit Brownian motion, a single molecule has a certain hitting probability at the receiver. This probability depends on the distance between the transmitter and the receiver, and the symbol duration ($P_{hit}(d, t_s)$). Assuming intra-molecule collisions have negligible effect on the molecule's movement, if n molecules are sent in a symbol duration, the number of molecules received within a symbol duration among these molecules is a random variable following a binomial distribution [7], [8]:

$$N_{c(n)} \sim Binomial(n, P_{hit}(d, t_s)) \quad (1)$$

As explained above, both CSK and MoSK methods decode the signal based on the total number of molecules received during a single symbol duration (N_T). Three sources contribute to this amount: the molecules belonging to the current symbol ($N_{c(n)}$), the residue molecules from the previous symbol ($N_{p(n)}$), and the molecules from other sources which can be summed up as noise (N_n). The second term can be calculated similar to the first term as the difference between two binomial random variables:

$$N_{p(n)} \sim Binomial(n, P_{hit}(d, 2t_s)) - Binomial(n, P_{hit}(d, t_s)) \quad (2)$$

We assume the noise in this communication system is Additive Gaussian White Noise (AGWN). Thus, the third term is also a random variable following a normal distribution with zero mean and σ variance

$$N_n \sim Normal(0, \sigma^2) \quad (3)$$

A Binomial distribution ($Binomial(n, p)$) can be approximated with a normal distribution ($\mathcal{N}(np, np(1-p))$) when p is not close to one or zero and np is large enough. Using this approximation, we can find N_T as the addition of three normal distributions.

The receiver decodes the symbol by comparing these N_T values with the threshold values of the modulation technique used. In CSK technique, there are 2^b-1 different threshold values where b is the bits per symbol rate. Using these thresholds, the receiver differentiates between different bit values. The threshold values for BCSK and QCSK implementations of the CSK technique are depicted in Figure 3. Since some molecules belonging to the previous symbol arrive at the receiver during the current symbol duration, different threshold values should be used based on the value of the previous symbol (S_p) to reduce erroneous decoding of the signal. Thus, in BCSK there are two threshold values whereas in QCSK there are twelve threshold values. On the other hand, in the case of MoSK techniques, a single threshold value is used both in BMoSK and QMoSK implementations.

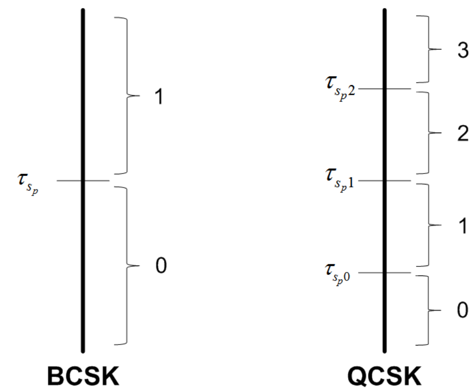

Figure 3. Symbol decoding for two implementations of the CSK technique (S_p: Previous Symbol)

We use a binary channel model for BCSK and BMoSK implementations, and a quadruple channel model for QCSK and QMoSK implementations in order to find the successful reception and incorrect decoding probabilities (Figure 4). Using the N_T value and the thresholds, these probabilities for the BCSK case can be found as follows if the current intended symbol is "0"

$$\begin{aligned} P_{R(S_p,0)} &= P(N_{p(n_{S_p})} + N_{c(n_0)} + N_n < \tau_{S_p}) \\ P_{X_1(S_p,0)} &= P(N_{p(n_{S_p})} + N_{c(n_0)} + N_n \geqslant \tau_{S_p}) \end{aligned}$$

and if it is "1"

$$\begin{aligned} P_{R(S_p,1)} &= P(N_{p(n_{S_p})} + N_{c(n_0)} + N_n \geqslant \tau_{S_p}) \\ P_{X_0(S_p,1)} &= P(N_{p(n_{S_p})} + N_{c(n_0)} + N_n < \tau_{S_p}) \end{aligned}$$

where S_p and S_c are the current and previous symbols respectively, $P_{R(S_p,S_c)}$ is the successful reception probability of S_c, and $P_{X_j(S_p,S_c)}$ is the incorrect decoding probability of S_c as "j".

For the QCSK case, the successful reception probabilities are

$$\begin{aligned} P_{R(S_p,0)} &= P(a_{S_p0} < \tau_{S_p0}) \\ P_{R(S_p,1)} &= P(a_{S_p1} < \tau_{S_p1}) - P(a_{S_p1} < \tau_{S_p0}) \\ P_{R(S_p,2)} &= P(a_{S_p2} < \tau_{S_p2}) - P(a_{S_p2} < \tau_{S_p1}) \\ P_{R(S_p,3)} &= P(a_{S_p3} \geq \tau_{S_p2}) \end{aligned}$$

and the incorrect decoding probabilities are

$$\begin{aligned} P_{X_0(S_p,S_c)} &= P(a_{S_pS_c} < \tau_{S_p0}) \\ P_{X_1(S_p,S_c)} &= P(a_{S_pS_c} < \tau_{S_p1}) - P(a_{S_pS_c} < \tau_{S_p0}) \\ P_{X_2(S_p,S_c)} &= P(a_{S_pS_c} < \tau_{S_p2}) - P(a_{S_pS_c} < \tau_{S_p1}) \\ P_{X_3(S_p,S_c)} &= P(a_{S_pS_c} \geq \tau_{S_p2}) \end{aligned}$$

where $a_{S_pi} = N_{p(n_{S_p})} + N_{c(n_i)} + N_n$.

The probabilities for BMoSK and QMoSK implementations can be calculated similarly and are omitted here to avoid repetition.

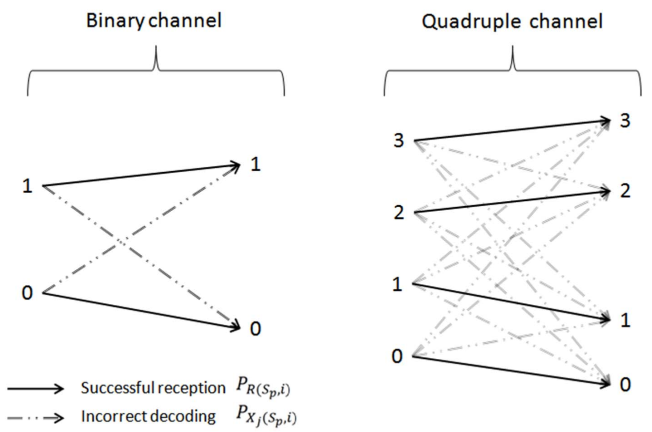

Figure 4. Channel models

Using these probabilities, we can find the mutual information, $I(X,Y)$, given the values for thresholds, distance, and the probability of hit during the current and next symbol durations [12]. By selecting ideal threshold values, the channel capacity (C) can be calculated using the maximum of mutual information as in Equation 5, where b stands for the bits per symbol rate used in the modulation technique.

$$C = \max_{\tau} I(X,Y) \quad (4)$$

$$= \max_{\tau} \sum_{Y=0}^{2^b-1} \sum_{X=0}^{2^b-1} \mathbf{P}_{X,Y}(x,y) \log_2 \frac{\mathbf{P}_{X,Y}(x,y)}{\mathbf{P}_X(x)\mathbf{P}_Y(y)} \quad (5)$$

IV. Performance Evaluation

We evaluate the performance of CSK and MoSK modulation techniques in terms of robustness against noises and the effect of transmission power. First, a communication system composed of a pair of devices as the transmitter and the receiver, is simulated. These devices communicate with each other using the CvD system. The messenger molecule used in the system is modeled after the human insulin hormone, and the propagation environment is chosen as water. First we set the symbol duration to a very high value (e.g., 36,000 seconds) and evaluate the hit times of the molecules at the receiver. Based on these hit times, we observe that after a certain duration, the hit times of the remaining molecules are widely spread over time. We choose the symbol duration (t_s) as this duration, rerun the simulations, and find the corresponding P_{hit} values over 150,000 trials. In order to take the ISI effect into account in the next step, the probability of hit values for single and two symbol durations are evaluated. The simulation parameters used and the resulting values are as given in Table I.

Using these P_{hit} values and the channel models explained in the previous section, the channel capacities of BCSK, BMoSK, QCSK, and QMoSK implementations under various Signal-to-noise (SNR) values are evaluated. We use the following

Table I
Simulation parameters

Parameter	Value
Diffusion coefficient (D)	$79.4\,\frac{\mu m^2}{s}$
Symbol duration (t_s)	$5.9\,sec$
Distance between transmitter and receiver (d)	$16\,\mu m$
Probability to hit in 1 symbol duration ($P_{hit}(d,t_s)$)	0.2223
Probability to hit in 2 symbol durations ($P_{hit}(d,2t_s)$)	0.2628

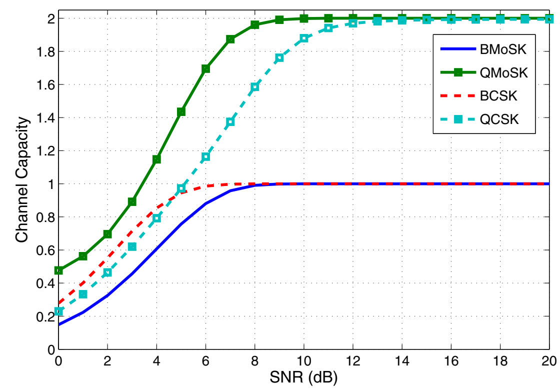

Figure 5. Channel capacity of different modulation techniques

SNR definition; the ratio between the average received signal power and the power of the noise. Average received signal power is found by using the P_{hit} values and the average number of molecules released for a single symbol (n_i). In case of CSK techniques, since there are multiple n_i values based on the bit value of each symbol, we take the average number of molecules per symbol where the probability of a symbol having each bit value is the same. Since we use AWGN, the power of the noise is defined as the variance of the normal distribution. The transition between number of molecules and the resulting energy in joules, we use the energy model developed in our previous paper [10].

According to the results given in Figure 5, all modulation techniques attain their theoretical channel capacity limits when the SNR level is high. The transmission power is defined as the number of molecules sent by the transmitter and is chosen as 1500 molecules. As SNR decreases, in case of the binary implementations, BCSK offers more robustness compared to BMoSK. Since, the noise in the channel is AWGN, the same amount of noise is applied to both molecule types in BMoSK. Thus, BMoSK is more affected by the noise than BCSK.

In case of quadruple implementations (QCSK and QMoSK), this trend changes and QMoSK exhibits higher noise tolerance than QCSK. This behavior is due to the number of threshold values used in these quadruple implementations. Since QMoSK uses a single threshold value, the channel capacity can be kept high by choosing a suitable threshold value even when the noise level is high. On the other hand, in QCSK finding suitable threshold levels to keep the channel capacity becomes harder as the noise level increases. After a certain noise level, the system cannot attain high successful reception probabilities regardless of the chosen threshold values. Therefore, the channel capacity drops.

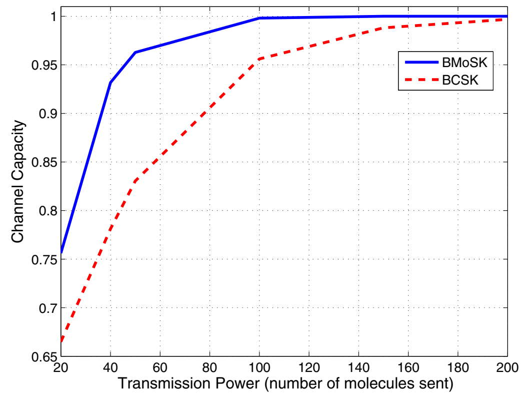

Figure 6. Effect of transmission power over channel capacity (Binary implementations of CSK and MoSK modulation techniques)

The transmission power also affects the performance of the modulation techniques. As seen in the Figures 6 and 7, while all modulation techniques attain high channel capacity values at high transmission power, the channel capacities decrease as the transmission power decreases. In both binary and quadruple implementations, the reduction in transmission power affects CSK techniques more than the MoSK techniques. These simulations are run with an SNR level of 20db. In order to keep SNR at 20db in all simulation runs, as the transmission power increases the variance of the noise also increases.

As the transmission power decreases, n_0 and n_1 get closer to each other. Thus, the successful reception probability of the intended symbol decreases. This behavior is more prevalent in QCSK since four different n_i values are used instead of two in BCSK and one in both MoSK implementations. Also, regardless of the technique used, the minimum transmission power required for high channel capacities increases as the bits per symbol rate of the modulation technique increases.

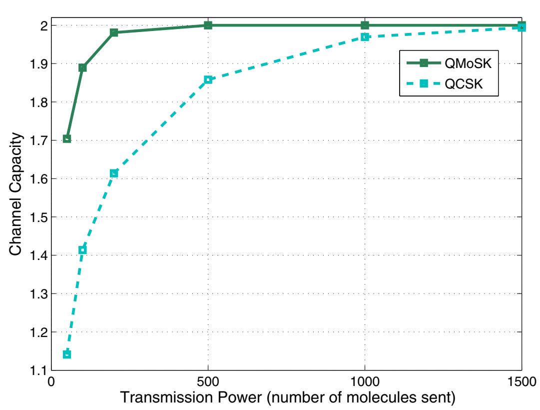

Figure 7. Effect of transmission power over channel capacity (Quadruple implementations of CSK and MoSK modulation techniques)

V. Conclusion

In this paper, we propose two modulation techniques for nanonetworks with communication via diffusion. The first technique, CSK, modulates the information via the variation in the concentration of the messenger molecules whereas the second technique, MoSK, utilizes different types of messenger molecules to represent the information. We abide with the classical modulation technique naming convention and name their derivatives according to the number of bits per symbol as BCSK, QCSK, BMoSK, and QMoSK techniques, respectively.

We evaluate the performances of these techniques in terms of susceptibility to noise and transmission power requirement. While both methods attain theoretical limits when the SNR ratio is high, BMoSK and QMoSK implementations exhibit more robustness against noise. Also, they require less power, which makes them more energy efficient in mapping bits onto messenger molecule symbols.

As the future work, we plan to extend this work by using a multi-node environment where there are concurrent transmissions between different transmitter and receiver couples. In this environment, in addition to the environmental noise, a transmission is further hindered by the interference caused by other communications.

Acknowledgment

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