Molecular Communications

A Project Report

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THESIS CERTIFICATE

This is to certify that the thesis entitled **Molecular Communications**, submitted by **Sadhana R**, to the Indian Institute of Technology, Madras, for the award of the degrees of **Bachelor of Technology & Master of Technology**, is a bona fide record of the research work carried out by her under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

Molecular communication is a new communication paradigm that could potentially aid in exchange of information between nanonetworks which form the basis of nanotechnology. Information is encoded on to the messenger molecules that are then transmitted into the fluid medum wherein they undergo diffusion and the molecules arriving at the receiver are then decoded to get back the original information. This is the Communication via Diffusion model that has been adopted in this thesis. The thesis also looks into some of the existing modulation techniques, namely, Concentration Shift Keying (CSK), Molecular Shift Keying (MoSK) and Time Shift Keying (TSK) and a study of their performance through simulation is presented. Finally, a new modulation scheme is proposed that aims to combine features of the existing techniques to improve performance.

KEYWORDS: Molecular Communications, Inverse Gaussian, Nanonetworks, Communication via Diffusion, Modulation Techniques

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ABBREVIATIONS

MC	Molecular Communication
CvD	Communication via Diffusion
ISI	Inter Symbol Interference
CSK	Concentration Shift Keying
MoSK	Molecular Shift Keying
TSK	Time Shift Keying
ML	Maximum Likelihood
PDF	Probability Density Function

NOTATION

D	Diffusion coefficient
d	Distance between transmitter and receiver
Δt	Time step
v	Velocity of medium
τ	Threshold

CHAPTER 1

INTRODUCTION

Molecular communication is a new communication paradigm by which exchang of information is done using molecules.

1.1 Origin

MC was originally inspired by biological systems. Communication occurs in nature through molecules. Efforts to mimic this method lead to research in the field of MC. Intercell communication in living organism happens via calcium signalling. The range of communication here is 1-100 nm. It helps cells coordinate to perform tasks such are contraction and secretion. Information is encoded onto the messenger molecules in the amplitude and frequency of the function describing the concentraion of the calcium ions. This information can be sent to cells which aren't in physical contact with the cell transmitting the information. The CvD system has been modelled along the same lines.[3]

1.2 Nanonetworks

Nanomachines are the basic functional units of a nanonetwork. They are capable of performing basic tasks such as computing, data storing, sensing at the nano- scale. But in order to form systems which have the capability to carry out much more complex tasks, we need nanomachines to coordinate with each other. It is necessary to aid the exchange of information between the machines to help them form a network.[1] MC is used to achieve this as the traditional methods of wired of wireless communication can not be used at the nano- level. Its applications include monitoring of health conditions, drug administering and in enabling lab-on-chip technology.[2]

1.3 Comparisons with Electromagnetic Communication

Signals are sent through to particles in the case of MC as compared to electromagnetic waves in traditional communcation and are therefore sensitive to and physical barrier that comes between the transmitter and the receiver. Signals are transmitted through a fluid medium and the propagation speed is much lesser in the case of MC. The energy consumption of electromagnetic communication is much greater than that of MC. Once the molecules have been released into the medium, their motion is completely random and can not be controlled.[1]

CHAPTER 2

MODELLING AND MODULATION TECHNIQUES

2.1 Communication via Diffusion System

In the CvD system, messenger molecules that are used to carry information are emitted by the transmitter into the medium wherein they undergo diffusion. The molecules that arrive at the receiver are decoded to extract the transimtted information. The number of mocules arriving in every time slot is compared with a threshold to deduce whether the transmitted symbol was ’0’ or ’1’. Due to the unpredictable nature of diffusion dynamics, some of the molecules may arrive at the receiver at a later time slot. This results in ISI which results in error while decoding.[4]

The motion of molecules through the medium is modelled by Brownian motion. The displacement of a molecule in any dimension is given by,

$$\Delta X = N(v\Delta t, \sqrt{2D\Delta t}) \tag{2.1}$$

where v is the velocity of the medium, D is the diffusion coefficient and Δt is the time step.

The duration of a time slot is taken to be the time by which 60% of the molecules arrive at the receiver. The symbol duration is given by t_s. This being the case, only the previous symbol causes significant interference.

The probability of transmitted molecules hitting the receiver is dependant upon the distance between the transmitter and receiver, $d$and symbol duration and is given by $P_{hit}(d, t_s)$.

If we consider that *n* are sent at the start of every symbol period, the number of molecules arriving in the current time slot is given by,

$$N_c = Binomial(n, P_{hit}(d, t_s)) \tag{2.2}$$

And the number of molecules arriving due to the previously transmitted symbol is given by,

$$N_p = Binomial(n, P_{hit}(d, 2t_s)) - Binomial(n, P_{hit}(d, t_s)) \tag{2.3}$$

Therefore, the total number of molecules arriving at the receiver in a given time slot, after approximation, is given by,

$$N_{hit} = N(nP_2, n[P_2(1 - P_2) - P_1(1 - P_1)) \tag{2.4}$$

where $P_1 = P_{hit}(d, t_s)$ and $P_2 = P_{hit}(d, 2t_s)$.

The binary channel model is given by,[4]

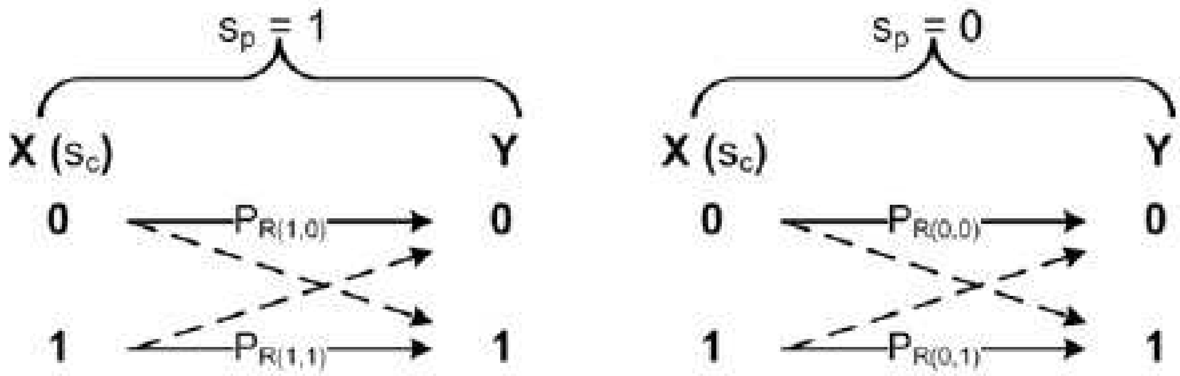

Figure 2.1: Binary Channel Model

where s_p and s_c are the previous and current transmitted symbols. $P_R(s_p, s_c)$ is the probability of correct detection of transmitted symbols given the previous and current symbols. Decisions at the receiver are made by comparing N_{hit} with a threshold value τ.

Capacity of this channel is given by,

$$C = max_{\tau} I(X,Y) = max_{\tau} \sum\sum P_{X,Y}(x,y) log_2 \frac{P_{X,Y}(x,y)}{P_X(x)P_Y(y)} \quad (2.5)$$

2.2 Modulation in CvD Systems

2.2.1 Concentration Shift Keying

CSK is analogous to Amplitude Shift Keying in MC. The information to be transmitted is encoded in the concentration of the molecules. In the case of Binary CSK, the number of molecules tranmitted at the beginning of every time slot is given by n_0 or n_1 when the symbol to be transmitted is 0 or 1, respectively. At the receiver, the number of arriving molecules in every time slot is compared with a threshold τ. If it exceeds the the threshold, the symbol is decoded to be 1, else 0.

This can be extended further to transmit one of 2^b symbols in every time slot to represent b bits. At the receiver, there are $2^b - 1$ threshold levels to decode the message sent. As the modulation order increases, the effect of ISI results in increased errors as the threshold levels are packed closer to each other and is more sensitive to interference.

A neat way to deal with ISI is to have different threshold levels based upon the previously received symbol. For example, in the case of Binary CSK, we have two different threshold values τ_1 and τ_2.[5]

2.2.2 Molecular Shift Keying

MoSK is a scheme where the information to be transmitted is encoded in the type of molecule. In the case of Binary MoSK, n molecules of A or B are transmitted at the beginning of every time slot when the symbol to be transmitted is 0 or 1, respectively. At the recever, the number of molecules arriving in every time slot is compared with a threshold τ. If the number of molecules of A or B is found to be greater the threshold, then the current symbol is decoded to be 0 or 1, respectively.

Higher order modulations are possible in the case of MoSK too. The number of the types of molecules used depends on the number of symbols that can be sent in every time slot. The number of thresholds at the receiver to decode remains one even for higher order modulations.[5]

2.2.3 Comparison between CSK and MoSK

The performance of CSK becomes significantly affected by ISI as the modulation order increses while MoSK performance is not affected to the same extent. This is because only one threshold level is used to make decision even when the modulation order increases. MoSK is more susceptible to chemical changes in the medium. The molecules used can reconfigure themselves and be converted to a molecule representing a whole new symbol. This increases the concentration of the molecules that was not originally transmitted, thus, resulting in errors while decoding.

The performance of both modulation improves when the number of transmitted molecules per symbol is increased. This is analogous to increasing the transmitted power.[5]

2.3 Additive Inverse Gaussian Noise Channel

Consider a one dimensional transceiver structure where the transmitter and receiver are separated by a distance d. Let the transmitter release one molecule into the medium, flowing with a velocity v, at time instant X. The arrival time of the molecule at the receiver is given by,

$$Y = X + N \tag{2.6}$$

where N has an inverse Gaussian distribution as follows:[6]

$$f_N(n) = \sqrt{\frac{\lambda}{2\pi n^3}} exp\left(-\frac{\lambda\,(n-\mu)^3}{2\mu^2 n}\right) \tag{2.7}$$

for $n > 0$ where $\mu = \frac{d}{v}$ and $\lambda = \frac{d^2}{D/2}$. The PDF is 0 for $n \leq 0$.

The arrival time of the molecules at the receiver can be described by this PDF only if the velocity of the medium from the transmitter to the receiver is positive $(v > 0)$ else there will be a non-zero probability that a molecule released into the medium will never arrive at the receiver.

The figure below shows the sample PDFs of the time of arrivals of the molecules released at time instant 0 for different values of D and v with constant $d = 1\mu m$. We can see that as velocity increase more number of molecules arrive at the receiver with a given time period. The same holds true for when the diffusion coefficient of the medium is increased.

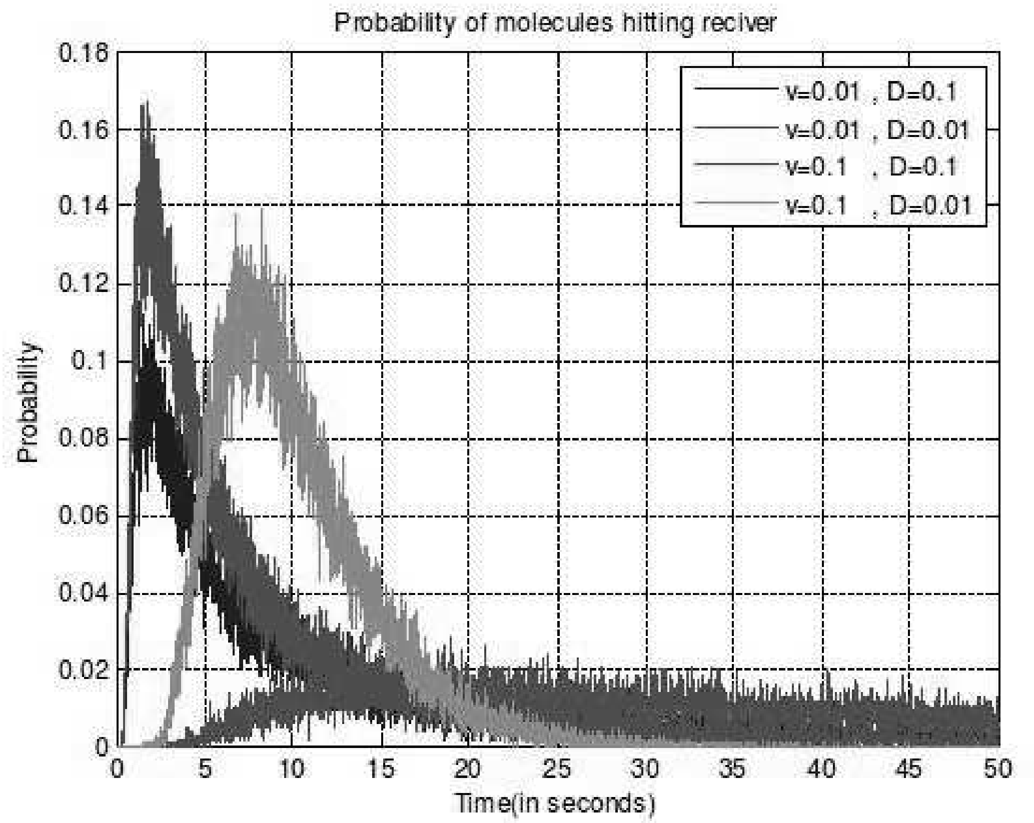

Figure 2.2: Inverse Gaussian PDFs

2.3.1 Time Shift Keying

TSK is a scheme where the information is encoded in the time instant of release (or the time delay in release) of a molecule to be tranmitted in every time slot. In the case of Binary TSK, a molecules is released at the beginning of a time slot or t_1 time units from the beginning of the time slot if the symbol to be transmitted is 0 or 1, respectively. At the receiver, the time of arrival of molecules is used to decode the trasnmitted signal with the help of an ML estimator.

The ML estimation is given by:

$$\hat{X}_{ML} = argmax_{t_i} f_{Y|X}\left(y|X = t_i\right) \tag{2.8}$$

or

$$\hat{X}_{ML} = argmax_{t_i} - \frac{3}{2} log(y - t_i) - \frac{\lambda}{2\mu_2} \frac{((y - t_i) - \mu)^2}{(y - t_i)} \tag{2.9}$$

for $y < t_i$ else $\hat{X}_{ML} = -\infty$.

In the case of Binary TSK, the $\hat{X}_{ML}$ value is calclulated $t_i = 0$ and t_1. The t_i value that gives the larger $\hat{X}_{ML}$ is decided to be the time instant of release and the decoded symbol is chosen accordingly.

This modulation scheme is found to perform better if, instead of one molecule per symbol, multiple molecules are transmitted. The number of molecules tranmitted power is a constant n. At the receiver, the average arrival time of the n transmitted molecules is used for decoding.

CHAPTER 3

PROPOSED MODULATION SCHEME

This modulation scheme combines features of CSK and TSK described above. The signal is sent across by encoding information into the number of molecules transmitted and the time instant of release of molecules in every time slot.

This method is analogous to using both the I and Q channels independently to transmit signals in traditional wireless communication. Two symbols are transmitted in every time slot. The first symbol modulates the time instant of release of molecules and the second symbol modulates the number of molecules transmitted.

At the receiver, the two symbols are decoded independently by taking into consideration the number of molecules arriving in every time slot and the average arrival time of the molecules received.

In this scheme, two symbols can be transmitted in every time slot. Decoding of one symbol does not affect the other. An ML estimator is used, as was the case in TSK, to decode the first symbol while thresholds are set, as was the case in CSK, to decode the second symbol.

A key feature of this scheme is that the transmitted power is significantly lesser when compared to the other schemes already giiven in literature. The average number of molecules used per symbol if half that of CSK when all other parameters remain constant.

CHAPTER 4

SIMULATIONS AND RESULTS

4.1 Model

We consider a one dimensional model where the transmitter is at $x = 0$ and the receiver is at $x = d$. The molecule released by the transmitter undergoes diffusion described by Brownian motion in the medium flowing with a velocity v. At every time step, the position of the molecule gets updated. If the position is found to be $x \geq 0$ at any time instant, then molecule is said to have reached the receiver then. It is assumed to be removed from the system when this happens.

The following figure shows the variation of the position of a molecule undergoing diffusion with time when $\delta t = 0.001s$, $v = 1\mu m/$ and $D = 2\mu m^2/s$:

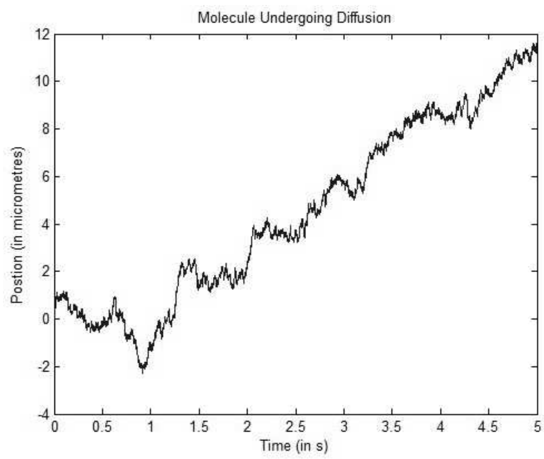

Figure 4.1: Brownian Motion

4.2 Symbol Period and Interference

The distance between the transmitter and receiver $d = 1\mu m$. Now, a large number of molecules (=1000000) are transmitted across the channel and t_s is taken to be the time by which $\approx 60\%$ of the molecules arrive at the receiver. This is found to be 0.53s for the given parameters.

The figure below shows the ratio of the transmitted molecules rarriving at the receiver at times given by multiples of t_s:

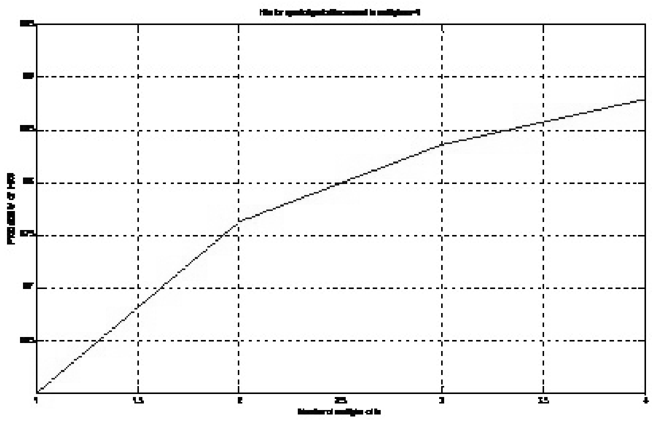

Figure 4.2: Molecules Arriving at the Receiver

As can be seen from the figure, if the symbol period is taken to be t_s, then significant interference is caused only due to two previously transmitted symbols.

4.3 CSK Simulation

For the following simulations, symbol period is taken to be $1.5t_s$. Now, significant interference is caused only due to the previously transmitted symbol which has to be considered during simulation. When the symbol to be transmitted is 0 or 1, the number of molecules released at the beginning of every time slot are $n_0 = 5$ or $n_1 = 10$, respectively. The average number of molecules transmitted is 7.5 per bit.

At the receiver, two thresholds t_0 and t_1 have to be fixed for comparing the number of molecules arriving in a time slot with to decode the transmitted symbol. If the previously decoded symbol is 0 then t_0 is the threshold to be used in the current time slot else t_1 is used.

Through Monte-Carlo simulations, the following plot was obtained which shows the variation of mutual information between the input and the output with t_0 and t_1.

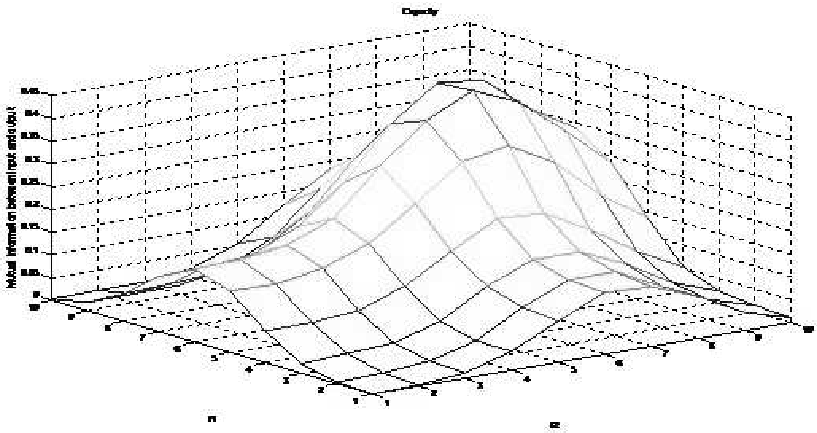

Figure 4.3: Mutual Information - CSK

Mutual information is found to be maximum when $t_0 = 6$ and $t_1 = 7$. These are taken to be the thresholds for decoding. A bit stream undergoes CSK modulation and the BER was found to be 0.1396.

The figure below shows the BER performance of CSK with increasing v. The BER performance improves with increasing velocity. Also, increasing the number of molecules transmitted per bit improves performance.

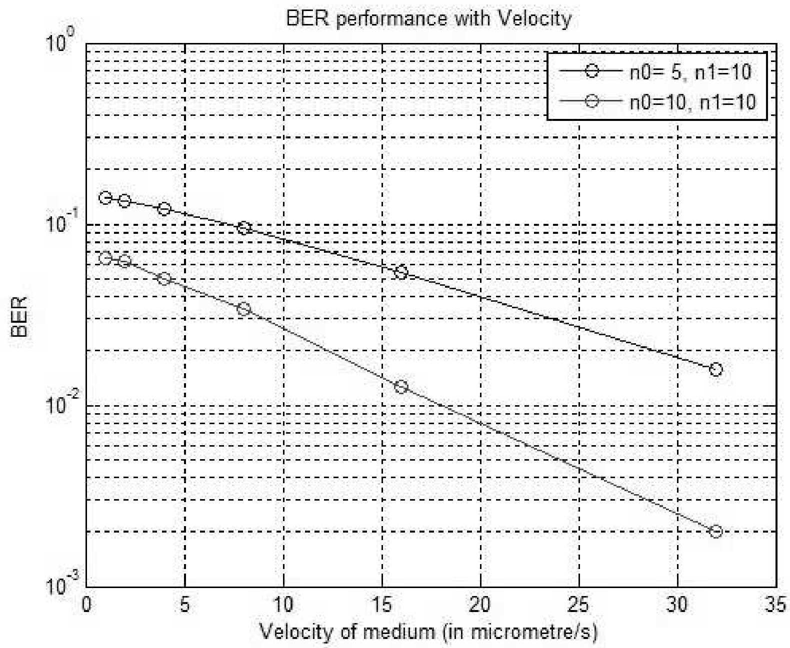

Figure 4.4: BER vs v - CSK

4.4 TSK Simulation

For the following simulations, symbol period is taken to be $3t_s$. Now, significant interference is caused only when the previously transmitted symbol is 1 which has to be considered during simulation. The time instant of release after a delay 0s or t_1s from the beginning of the time slot if the symbol to be transmitted is 0 or 1, respectively. The number of molecules transmitted per symbol is 5.

At the receiver, the average time of arrival of the $n = 5$ molecules are used to get decode the transmitted symbol using a ML estimator.

Through Monte-Carlo simulations, the variation of mutual information with t_1 is shown below:

Mutual information is found to be maximum at $t_1 = 0.59s$. This is taken to be the time instant of release of molecules in a time slot when the symbol to be transmitted is 1. A bit stream undergoes TSK modulation and the BER is found to be 0.0976.

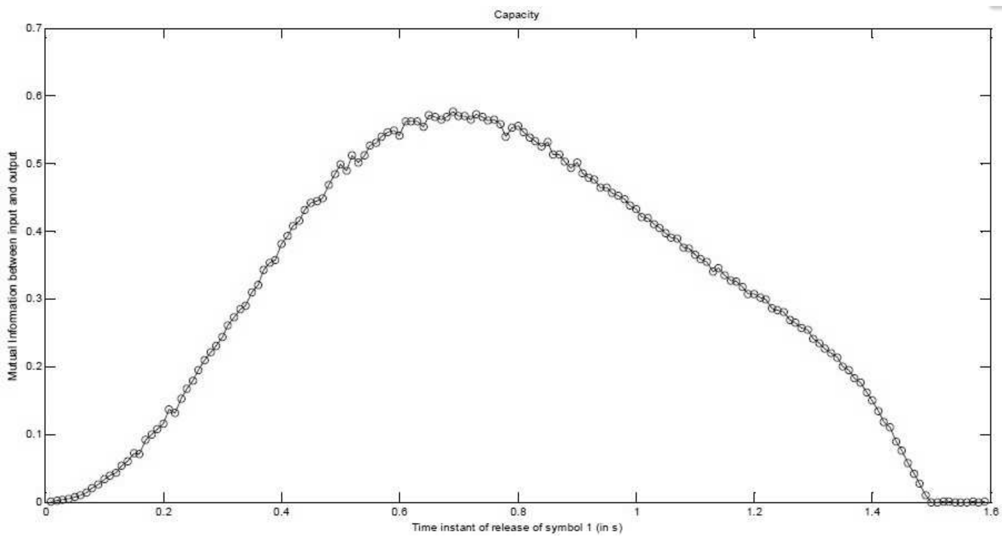

Figure 4.5: Mutual Information - TSK

The figure below shows the BER performance of TSK with increasing v. The performance improves with increasing velocity and with the number of transmitted molecules per symbol.

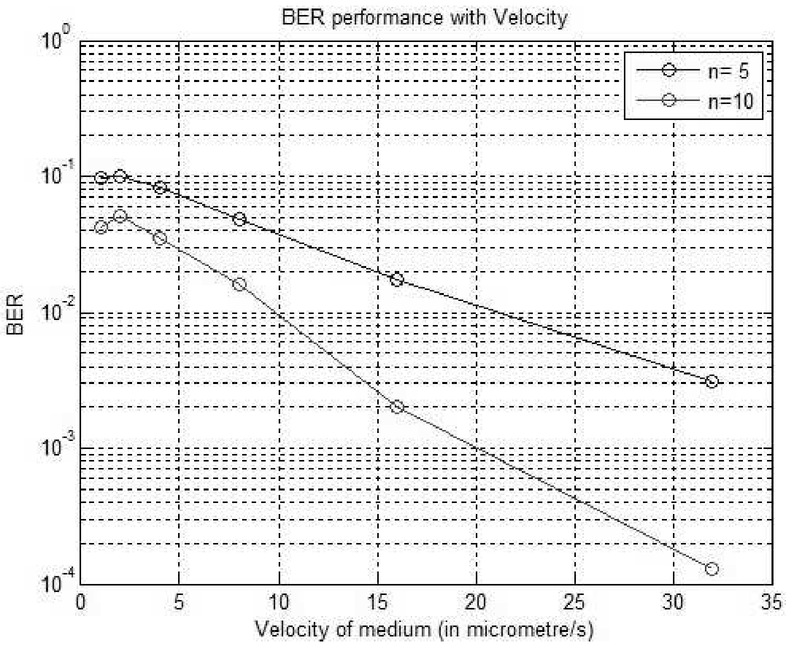

Figure 4.6: BER vs v - TSK

4.5 Proposed Modulation Simulation

For the following simulations, the symbol period is taken to be $3t_s$. Two bits are transmitted in every time slot with the first modulating the time of release of molecules and the second, the number of molecules released. The average number of molecules transmitted per bit is 3.25 which is half as that of BCSK. The encoding at the trasnmitter is carried out as follows:

Table 4.1: Proposed Modulation Scheme Encoding

Symbol	Number of molecules transmitted	Time instant of transmission $(in s)$
$[00]$	5	0
$[01]$	10	0
$[10]$	5	0.59
$[11]$	10	0.59

Through Monte-Carlo simulations, the following graph was obtained showing the variation of mutual information between input and output with the threshold to decode the second bit and the time instant of release of molecules according to the first bit.

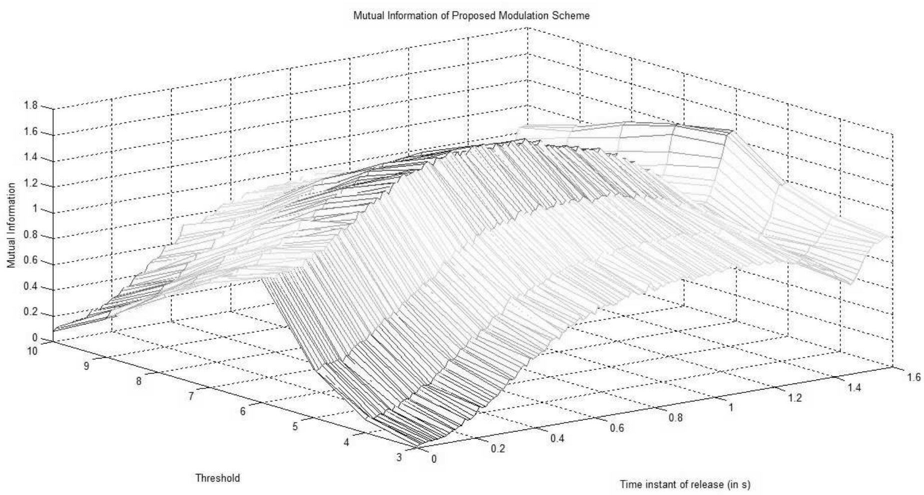

Figure 4.7: Mutual Information - Proposed Modulation

Mutual information was found to be maximum when the threshold is 8 and the time of release of molecules when the symbol 1 is to be transmitted is 0.73s. We fix these values and an input bit stream is sent through. BER was found to be 0.0396 which is significantly better than the BER performance of BCSK for the same data rate. Also, the average number of molecules transmitted per bit here is 3.75 which is half as that of CSK.

The figure below shows the BER performance of the porposed modulation scheme with increasing v. The performance, as expected, improves with increasing velocity.

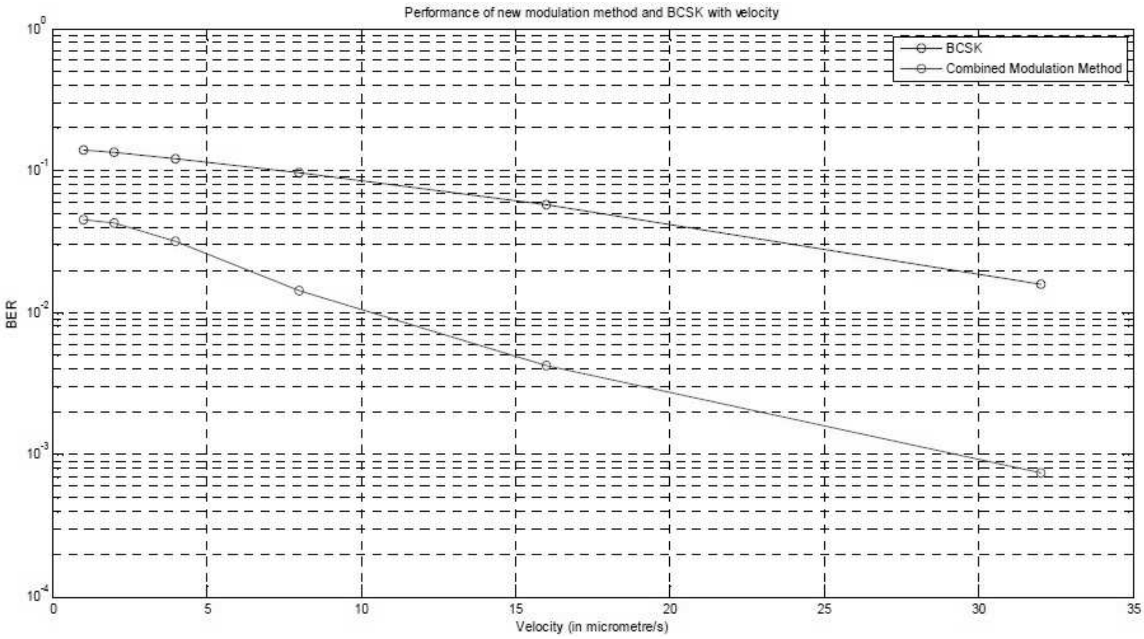

Figure 4.8: BER vs v - Proposed Modulation

The above figure compares the performance of the proposed modulation scheme and BCSK. The proposed modulation scheme outperforms CSK for the same data rate and half the transmission power. The BER performance is found to improve with increasing velocity as is to be expected.

A comparison with TSK is not necessary, since, for the same data rate, the BER performance of TSK is extremely poor as there isn't sufficient delay between time insatants of release of molecules which results in increased errors while decoding with an ML estimator.

CHAPTER 5

SCOPE OF PROJECT

This thesis has made a comprehensive study of the existing modulation techiniques used for MC and the modelling of the CvD system for MC. From the results obtained through simulations of the existing modulation schemes a new scheme has been proposed that combines features of two of the existing methods to give better performance. The key aspect of this new modulation scheme being that it is much more energy efficient when compared to others. This is important since nanomachines are expected to be self-sustaining i.e. they have to produce molecules required for communication. Reducing the number of molecules used to transmit a signal greatly reduces the load on the nanomachine.

5.1 Future work and Extensions

The proposed modulation scheme described here is yet to be optimized taking into account interference from previously decoded symbol. This can results in significantly better performance, if done. The channel can be modelled as a L-tap channel depending upon the symbol period chosen. This will allow for concepts being borrowed from traditional communication and can potentially deliver better performance with ease. This will allow for informaion on memory of the channel to be used in a manner that is easy to handle. Interfernce can then be dealt with efficiently even when channel conditions like v are canstantly changing.

CHAPTER 6

CONCLUSIONS

A modulation scheme exists which is analogous to transmitting signal on the I and Q channels in traditional communication in MC. By combining features of CSK and TSK, it is possible to modulate information onto the concentration and the timing of release of molecules. The resulting scheme is found to perform better when compared to the others and is also more energy efficient.

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