Enhanced Inter-Symbol Interference Cancellation Scheme for Diffusion Based Molecular Communication using Maximum Likelihood Estimation

Prachi Raut[1] and Nisha Sarwade[2]
Department of Electrical Engineering, Veermata Jijabai Technological Institute,
Mumbai 400019 Maharashtra, India
[1][e-mail: rautps@gmail.com]
[2][e-mail: nishasarvade@vjti.org.in]
*Corresponding author : Prachi Raut

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Abstract

Nano scale networks are futuristic networks deemed as enablers for the Internet of Nano Things, Body area nano networks, target tracking, anomaly/ abnormality detection at molecular level and neuronal therapy / drug delivery applications. Molecular communication is considered the most compatible communication technology for nano devices. However, connectivity in such networks is very low due to inter-symbol interference (ISI). Few research papers have addressed the issue of ISI mitigation in molecular communication. However, many of these methods are not adaptive to dynamic environmental conditions. This paper presents an enhancement over original Memory-1 ISI cancellation scheme using maximum likelihood estimation of a channel parameter (λ) to make it adaptable to variable channel conditions. Results of the Monte Carlo simulation show that, the connectivity (P_{conn}) improves by 28% for given simulation parameters and environmental conditions by using enhanced Memory-1 cancellation method. Moreover, this ISI mitigation method allows reduction in symbol time (Ts) up to 50 seconds *i.e.* an improvement of 75% is achieved.

Keywords: Molecular communication, Inter-symbol interference, Connectivity, Maximum likelihood estimation

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1. Introduction

Nano scale networks are communication networks in which node sizes are in nano regimes (1-100 nm) [1]. Nodes of these networks are nano machines (NMs) or nano devices capable of sensing and actuating, simple computing and communications. Such NMs networks can be used for applications including the Internet of Nano Things [2], target tracking [3], anomaly/ abnormality detection [4,5], Body area nano network [6,7] , neuronal therapy and drug delivery [8]. Due to small size and limited capabilities of NMs, electro-magnetic communication may not be suitable in nano networks. An alternative energy efficient communication technology compatible with small size of the NMs needs to be employed. Molecular communication (MC) (information transmitted by messenger molecules) appears to be the best communication technology for nano scale networks [1]. MC is used in biological systems for communication. For example, Calcium ion signaling amongst the cells of human body [9] and pheromone communication used in some species of insects [10]. The molecular transport can be either active (using molecular motors) or passive (by diffusion). In this paper, diffusion based MC is considered.

In MC by diffusion, information which is encoded either in concentration of messenger molecules (Concentration Shift Keying (CSK)) or in the type of messenger molecules (Molecular Shift Keying (MoSK))[11]. Transmitter emits required number (or type) of molecules, which diffuse through fluidic media. (For example, air and water). Some of these molecules hit the receiver and get attached to the specific receptors present on surface of the receptors. This type of attachment is called Ligand-receptor binding [12]. Receivers then perform decoding to detect the transmitted symbol.

The molecular transport by diffusion is stochastic and exhibits large delay. This imposes upper limit on data rate achieved in MC. If data rate exceeds this upper limit, inter-symbol interference (ISI) occurs, resulting in erroneous detection of symbols. A particular result in our previous publication [13] shows that the connectivity (P_{conn}) (probability of two nodes being connected to each other) in MC based NMs network degrades by 10% (distance between receiver and transmitter being 6 cm) due to ISI alone.

Moreover, molecular transport in MC is a function of environmental parameters as temperature (*Temp*) and physical obstructions concentration (X). This, in turn, affects the P_{conn} [14]. Hence, it is essential to design ISI mitigation method for MC which in adaptive to environmental conditions.

Several methods have been suggested for ISI mitigation in literature including Memory-1 ISI cancellation method [15]. Although this method is simple and avoids complex operations, it is not adaptive to dynamic environmental conditions. Objective of this paper is to present an enhancement over original Memory-1 ISI cancellation to make it adaptable to variable channel conditions (which are characterized by parameter λ, explained in section 2.3). Maximum likelihood estimation (MLE) is used to determine the value of λ at the starting of every new communication. This helps in accurate estimation and cancellation of ISI from received signal and in turn, improves P_{conn}. Performance of enhanced Memory-1 cancellation method is measured using Monte Carlo simulation in MATLAB for various values of X and *Temp*. It is observed that P_{conn} improves by using enhanced Memory-1 cancellation scheme for specific values of *Temp* and X.

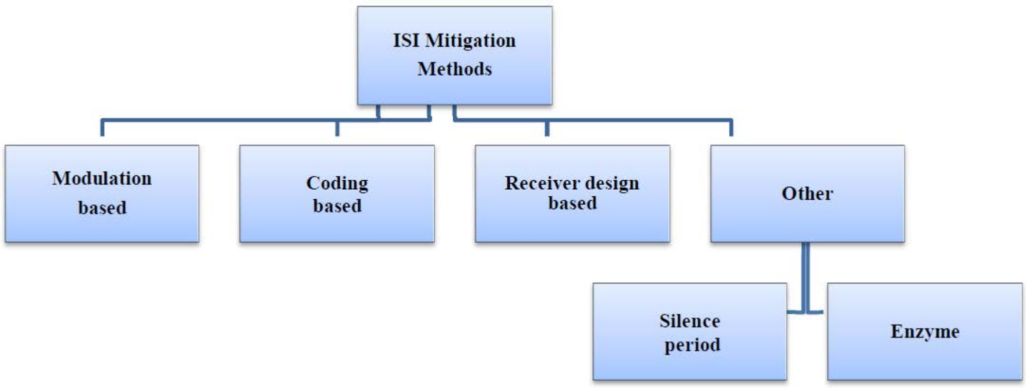

Fig. 1. Classification of ISI mitigation techniques in molecular communication

Rest of the paper is organized as follows: Section 2 presents a review of various ISI mitigation methods in MC. Section 3 describes proposed ISI cancellation method followed by results and discussions in section 4. Conclusion and future scope is described in section 5.

2. Literature Review

This section reviews ISI mitigation methods for diffusion based MC published so far. **Fig. 1** shows classification of the techniques surveyed here.

2.1 Modulation based techniques

Two basic types of modulation used in MC are - Concentration Shift Keying (CSK) and Molecular Shift Keying (MoSK). A specific case of CSK is OOK (On-Off Keying) where no molecules are transmitted for symbol 0. In CSK, if symbol 0 is occurring after symbol 1, residual molecules from previous symbol may result in erroneous detection of the later symbol, due to long tail of a diffused pulse. MoSK faces no such problem but required transmitter power is high compared to CSK since same numbers of molecules must be transmitted for either symbol. Moreover, two types of messenger molecules and corresponding receptors are needed.

Arjmandi *et al* [16] have proposed a new modulation method, which is a combination of CSK and MoSK. The transmitter uses molecules of type A_1, in odd time slots, and of type A_2 in even time slots. The use of two molecule types resembles MoSK but in this technique, molecule type is used for indicating odd and even time slots. To convey information in each time slot, different diffusion rates are used (similar to CSK). As the molecule types are different in two subsequent time slots, the previous symbol interference does not arise and since the data is not encoded in the molecule types, the number of molecule types does not increase with number of bits in a symbol. Numerical results indicate this scheme has a lower probability of error compared to CSK and MoSK.

Pudasaini *et al* [17] have suggested Zebra-CSK modulation scheme, which adds inhibitor molecules in CSK-modulated molecular signal to selectively suppress ISI causing molecules. Temporal alternation of messenger molecules and inhibitor molecules is also suggested.

Numerical results show that Zebra-CSK not only enhances capacity of the molecular channel but also reduces symbol error probability.

Molecular transition shift keying (MTSK) was suggested by Tepekule *et al* [18]. Bit 0s are encoded by the absence of the messenger molecules, and bit 1s are encoded by using two different types of molecules, denoted as type *A* and type *B*. The choice of the molecule type depends on the value of the following symbol in the message sequence. Type *A* molecules are released if the next symbol is 0 and type *B* molecules are released if the symbol is 1. Emitting type *B* instead of type *A* molecules before each bit 0 reduces the ISI induced by type *A* molecules on each bit 0. Similarly, since type *B* molecules are only emitted before a bit 0, their accumulation in the channel is less than the case where CSK is employed by emitting only type *B* molecules. As a result, ISI observed by each 0 bit is decreased compared to the case where CSK is employed.

2.2 Coding based techniques

In electromagnetic communication, channel codes are commonly used for ISI mitigation. Block codes (e.g. Hamming codes) and convolution codes are the major classes of channel coding which improve channel capacity. However, decoding could be computationally intensive. In addition, NMs must be able to encode and decode messages using these codes with minimum energy requirements. While considering these constraints, following coding techniques have been put forward.

Yeh *et al* [15] have argued that the commutative Hamming distance cannot be considered as a good metric for MC due to "Crossover" effect (change in the symbols arrival sequence) and proposed a new distance metric based on error probability. A molecular distance metric between two molecular sequences *x* and *y* has been defined as

$$d(x,y) = -\log(P\{x \rightarrow y\}) \quad (1)$$

where $P\{x \rightarrow y\}$ is the probability of *x* being interpreted as *y*.
Further, a new channel coding technique- "ISI-free codes" is devised for MoSK modulation. The idea is used to use "proportion" of symbols in a code word rather than "position" of it. For example, code words 00010 and 00001 are considered to represent same symbol. From the results, it is observed that, ISI-free codes have lower BER than the conventional convolution codes.

Leeson and Higgins [19] have achieved a coding gain of ~ 1.7 dB at transmission distances of 1 μm in MC based network using simple Hamming codes. It is also shown that these simple error correction codes can deliver a benefit in terms of energy usage for transmission distances of upwards of 25 μm for receivers of a 5 μm radius.

2.3 Receiver based techniques

Use of modulation or channel codes is employed at the transmitter side where channel conditions are unknown. Channel equalizers are functional blocks whose response is inverse of channel response. Equalizers use recursive algorithms to adjust their response according to channel conditions. Implementation of equalizers is complex and computationally expensive. Conventional equalization schemes such as zero-forcing or minimum mean square error (MMSE) estimation schemes need statistical knowledge of the channel.

The random nature of molecular movement makes these equalization schemes difficult to use in diffusion based MC. Also, computational constraints of NMs implementation of such schemes in nano scale could be challenging.

Yeh *et al* [15] have suggested decision feedback equalization (DFE) scheme that uses the detection history of past symbols to eliminate ISI. In proposed "Memory-1 cancellation scheme", the main idea is to calculate the expected number of interfering molecules with the help of decision history of only the last symbol (hence the name "Memory-1") and recorded number of molecules received in previous symbols. The receiver can then subtract that number from the received number of molecules within the current symbol period, and thus the communication reliability can be improved. The method assumes CSK modulation with a constant symbol period *Ts*. It is known that if the emitted molecules follow the Brownian motion, the propagation time *T* (from the transmitter to the receiver) of a molecule in a one-dimensional space is inverse Gaussian (IG) distributed with probability density function (PDF) as shown below:

$$f_T(t) = \begin{cases} \sqrt{\dfrac{\lambda}{2\pi t^3}} \quad exp\left(\dfrac{-\lambda(t-\mu)^2}{2\mu^2 t}\right) ; t > 0 \\ 0 \; ; \; t \leq 0 \end{cases} \tag{2}$$

Where $\lambda = d^2/2D$ (Unit: Seconds) is a shape parameter and $\mu = d/\upsilon$ is the mean of T where D is the diffusion coefficient, d is the transmission distance, and υ is a positive drift velocity in the medium.

Cumulative distribution function (CDF) of T is denoted by $F_T(t)$. The system is operated using the binary amplitude modulation that emits L_1 molecules for bit 1 and L_0 for bit 0. If the number of particles received during the $(i-1)^{th}$ symbol period is estimated to be $\hat{l}_{i-1}$ (where $\hat{l}_j \in \{L_0, L_1\}$), then the expected number of molecules from the $(i-1)^{th}$ symbol interfering the i^{th} symbol would be $\hat{l}_{i-1} \cdot [F_T(2Ts) - F_T(Ts)]$. The receiver then subtracts the number from the received number of molecules of the i^{th} symbol duration and then makes decision based on the result.

In conventional communication systems corrupted by stationary additive white Gaussian noise, the optimum receiver consists of a matched filter as a demodulator followed by a detector that recovers the transmitted information using a minimum Euclidean distance metric. As shown by ShahMohammadian [20], diffusion-based molecular communication channel, noise is non-stationary and signal dependent which means that the matched filter is no longer optimum. Hence to minimize the probability of error, the authors have suggested, maximum likelihood criteria based Viterbi algorithm for detection for a MoSK based system. To make it computationally simple only single sample from previous transmission is taken into account. It is shown that the proposed optimum receiver is able to effectively reduce the impact of ISI.

Tepekule *et al* [18] have proposed an energy efficient decision feedback filter for ISI mitigation. DFF calculates the optimum threshold value for the symbol in question and updates the decision threshold for each sample by using the previously estimated bits. When DFF was compared with the MMSE equalizer in terms of bit error rate, memory length, and computational complexity via Monte Carlo simulations, it was concluded that DFF requires more memory to reach the same error rate as that of the MMSE equalizer, but since calculating the optimal threshold value has computational complexity at the order of $O(1)$, DFF becomes more advantageous when energy efficiency is a priority.

2.4 Other techniques

Chou [21] has suggested the use of silence period to reduce ISI. It also helps the decoder to return to an internal state before it can start to decode the next symbol. However, use of this technique also reduces data rate. Noel *et al* [22] recommend adding enzymes to the propagation environment of a diffusive molecular communication system as a strategy for

Table 1. Comparison of various ISI mitigation methods

Reference	Type	Advantages	Limitations
Arjmandi *et al* [16]	Modulation (MoCSK)	• Simple implementation • Scalable • Lower bit error rate than CSK and MoSK	• Two types of messenger molecules needed • Channel conditions not considered
Pudasaini *et al* [17]	Modulation (Zebra-CSK)	• Better bit error rate than CSK	• Two types of messenger molecules and inhibitor molecules required • Performance depends on efficiency of inhibitor molecules • Not adaptive to channel conditions
Tepekule *et al* [18]	Modulation (MTSK)	• For same average power, bit error rate of MTSK is better than that of CSK and MTSK	• Two types of messenger molecules needed • Channel conditions not considered
Yeh *et al* [15]	Coding	• Simple codes • Scalable • Bit error rate better than convolution codes	• Can be used only with MoSK • Energy requirements ion not known • Not adaptive to channel conditions
Leeson and Higgins [19]	Coding	• Coding gain of ~ 1.7 dB at transmission distances of 1 μm in achieved using simple Hamming codes • Energy requirements for encoding/decoding computed	• Channel conditions not considered • Computationally intensive
Yeh *et al* [15]	Receiver based (Decision feedback equalizer)	• Can be used with CSK,OOK • Simple implementation • symbol error rate improved	• Not adaptive to channel conditions

Reference	Type	Advantages	Limitations
ShahMohammadian *et al* [20]	Receiver based (ML based decoder)	• Optimum receiver designed considering non-stationary, signal-dependant noise • BER of proposed scheme is found to be lower even in No ISI case	• Complex implementation • History of previous symbols needed • Can be used only with MoSK • Energy considerations not given
Tepekule *et al* [18]	Receiver based (Decision feedback filter)	• Energy efficient • Optimum threshold for each symbol computed • Lower computation required than MMSE equalizer	• DFF requires more memory to reach the same error rate as that of the MMSE equalizer
Chou [21]	Silence period	• No extra functions required • Receiver and transmitter need not be in synchronization	Can be only used in FSK modulation
Noel *et al*[22]	Enzymes based	• Enzymes may be recycled. Hence cost-effective • Waiting period is reduced. Increase in data rate	• Use of enzymes required • External control required for amount of enzymes

mitigating ISI. The enzymes form reaction intermediates with information molecules and then degrade them so that they have a smaller chance of interfering with future transmissions.

Table 1 summarizes ISI mitigation methods for diffusion based MC. The receiver based techniques of ISI mitigation are more effective since they take statistical information about the channel and previous decision histories into account. However, implementation of such algorithms could be computationally expensive. Memory-1 ISI cancellation scheme by Yeh *et al* [14] is simple to implement since it does not use any recursive algorithm and needs detection history of only previous symbol. Although to estimate number of ISI molecules, accurate knowledge of CDF of T is required. Since the CDF depends on parameter λ, it is needed to estimate the λ (which may vary depending on environmental conditions as temperature and distance between transmitter and receiver).

Therefore, we suggest an enhancement over the said scheme by including a parameter (λ) estimation block which helps in accurate determination and cancellation of ISI.

3. Enhanced Memory-1 Cancellation Scheme

As discussed in previous section, Memory-1 cancellation scheme determines the amount of ISI molecules in the reception with the help of CDF of first passage time *T*. Accuracy of this scheme depends on accurate knowledge of channel parameter λ. However, Yang *et al* [15] have not suggested any method of estimating the λ value. Since λ is a function of diffusion coefficient, it varies with environmental parameters as temperature (*Temp*) and concentration of physical obstructions (*X*) in the channel. Hence, accurate and timely measurement of λ is needed to estimate the number of ISI molecules. Therefore, we propose an enhancement over Memory-1 ISI cancellation scheme by augmenting it with a maximum likelihood estimator for λ. Estimating λ before start of every new communication, leads to accurate ISI determination and cancellation.

3.1 Maximum likelihood estimator (MLE) for λ

Propagation time (*T*) of diffusing molecules follows IG distribution as shown in (2). If there is no drift in the medium υ=0, the mean becomes infinite and PDF of *T* assumes Levy distribution [23].

$$p(T) = \begin{cases} \sqrt{\frac{\lambda}{2\pi T^3}} \;\; exp\left(\frac{-\lambda}{2T}\right) \;\; ; T > 0 \\ 0\,; T \le 0 \end{cases} \tag{3}$$

To estimate λ, large set of observed T^k values (T^1, T^2, T^3,.....,T^N) must be available. As per MLE principle, which value of λ has resulted in these observations is to be determined.
$p(T|\lambda)$ is the probability of getting observations *T*, for a given value of λ:

$$p(T|\lambda) = \prod_{k=1}^{N} p(T^k|\lambda) \tag{4}$$

Now, ML estimate of λ ($\hat{\lambda}$) is that value of λ which maximizes the likelihood of $p(T|\lambda)$. It is easier to maximize $log(p(T|\lambda))$. Hence

$$\widehat{\lambda} = argmax(\log(p(T|\lambda))) \tag{5}$$

Substituting $p(T|\lambda)$ value from (4) and expanding *log(.)* expression

$$\hat{\lambda} = argmax(\textstyle\sum_{k=1}^{N} log(p(T^k|\lambda)) \tag{6}$$

Substituting $p(T^k|\lambda)$ from (3),

$$\widehat{\lambda} = argmax(\textstyle\sum_{k=1}^{N} \left(log\left(\sqrt{\frac{\lambda}{2\pi(T^k)^3}} exp\left(\frac{-\lambda}{2T^k}\right)\right)\right)) \tag{7}$$

Expanding above expression and solving logarithm terms :

$$\hat{\lambda} = argmax\left(\textstyle\sum_{k=1}^{N} \;(log\left(\sqrt{\frac{\lambda}{2\pi(T^k)^3}}\right) - \frac{\lambda}{2T^k})\right) \tag{8}$$

Now, to determine maximum value of the expression inside the bracket, take derivative and equate it to zero.

$$\frac{\partial}{\partial\lambda}\left(\sum_{k=1}^{N}(log\left(\sqrt{\frac{\lambda}{2\pi(T^k)^3}}\right)-\frac{\lambda}{2T^k t})\right)=0 \quad (9)$$

Solving above equation further,

$$\left(\sum_{k=1}^{N}(\frac{\partial}{\partial\lambda}\log\left(\sqrt{\frac{\lambda}{2\pi(T^k)^3}}\right)-\frac{\partial}{\partial\lambda}\frac{\lambda}{2T^k})\right)=0 \quad (10)$$

After taking the derivatives,

$$\sum_{k=1}^{N}\left(\sqrt{\frac{2\pi(T^k)^3}{\lambda}}\cdot\left(\frac{1}{2}\right)\cdot\left(\frac{\lambda^{-1/2}}{\sqrt{2\pi(T^k)^3}}\right)-\frac{1}{2(T^k)^3}\right)=0 \quad (11)$$

Simplifying above equation

$$\sum_{k=1}^{N}\frac{1}{2\lambda}-\frac{1}{2T^k}=0 \quad (12)$$

$\hat{\lambda}$ value is determined by rearranging terms of above equation

$$\hat{\lambda}=\frac{N}{\sum_{t=1}^{N}\frac{1}{T^k}} \quad (13)$$

However, one more condition must be satisfied to prove that $\hat{\lambda}$ determined in above equation is a maximum value. The condition is as follows:

$$\frac{\partial^2}{\partial\lambda^2}p(T|\lambda)<0 \quad (14)$$

Now, $\frac{\partial^2}{\partial\lambda^2}p(T|\lambda)=\frac{-1}{2}\lambda^{-2}$; which is less than zero, since λ pertains to time which is always a positive quantity.

The Cramer-Rao lower bound (CRLB) is the lower bound for estimation variance which is considered as a benchmark for comparing the performance of different estimators. In order to derive the CRLB for an estimator, it must be shown that the regularity condition is satisfied.

$$var(\lambda)\geq\frac{1}{-E[\frac{\partial^2}{\partial\lambda^2 p}p(T|\lambda)]} \quad (15)$$

$$var(\lambda)\geq\frac{1}{-[\frac{-1}{2}\lambda^{-2}]} \quad (16)$$

$$var(\lambda)\geq 2\lambda^2 \quad (17)$$

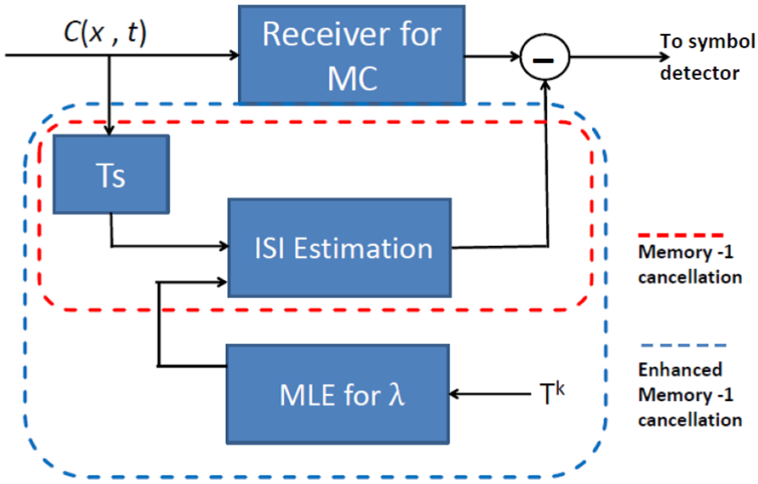

Fig. 2. Enhanced Memory-1 ISI scheme

3.2 ISI cancellation

Fig. 2 shows original (enclosed by red dotted line) as well as enhanced Memory-1 ISI cancellation scheme (enclosed by blue dotted line). Since binary CSK modulation is considered, received molecular concentration $C(d,t)$ is used to detect a symbol. (In this case, one symbol just consists of one bit). A single memory element holds the value of $\hat{l}_{i-1}$ *i.e.* number of molecules received during previous symbol time.

4. Results and Discussions

Performance of maximum likelihood estimator for λ developed in previous section is measured using MATLAB. CRLB and mean squared error is computed for various values of N (Number of samples) for λ = 200, 250 and 300 seconds. The result is plotted in **Fig. 3**. It is observed that with increasing N, Mean Squared Error (MSE) reduces. Also for given simulation parameters, CRLB presents a lower bound on MSE values.

Fig. 4 shows performance of enhanced Memory-1 cancellation scheme in improving P_{conn} for various values of *Temp*. Computation of P_{conn} is done as per the connectivity model developed in [13]. In each case, P_{conn} has increased following cancellation of ISI. At 25°C, 14-15% improvement in P_{conn} is observed. As *Temp* increases, rapid degradation of molecules reduces ISI. Hence ISI cancellation doesn't provide considerable performance improvement. However, P_{conn} increases rapidly and reaches its maximum value (99.9%), at lower symbol times. At 35°C, T_s of 50 seconds results in P_{conn} = 96.5%. This is much better than T_s = 200 seconds considered earlier. This results in reduction in symbol time by 75%.

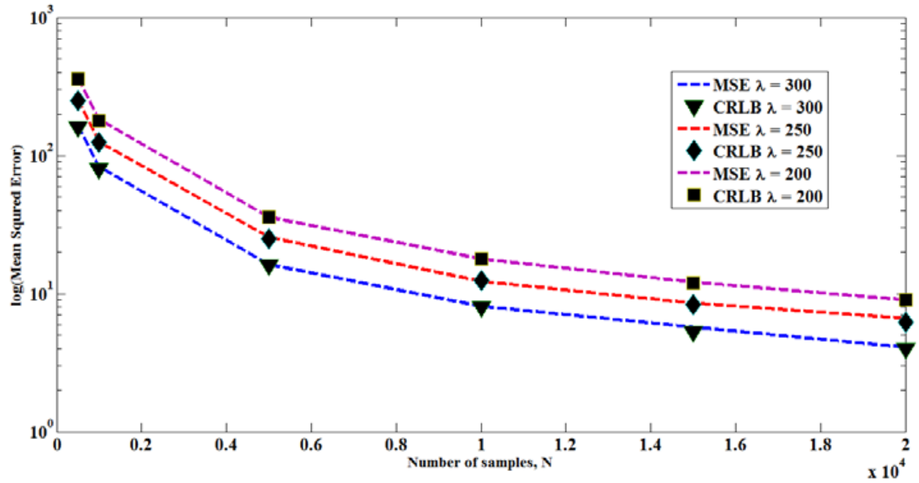

Fig. 3. Performance of λ estimator

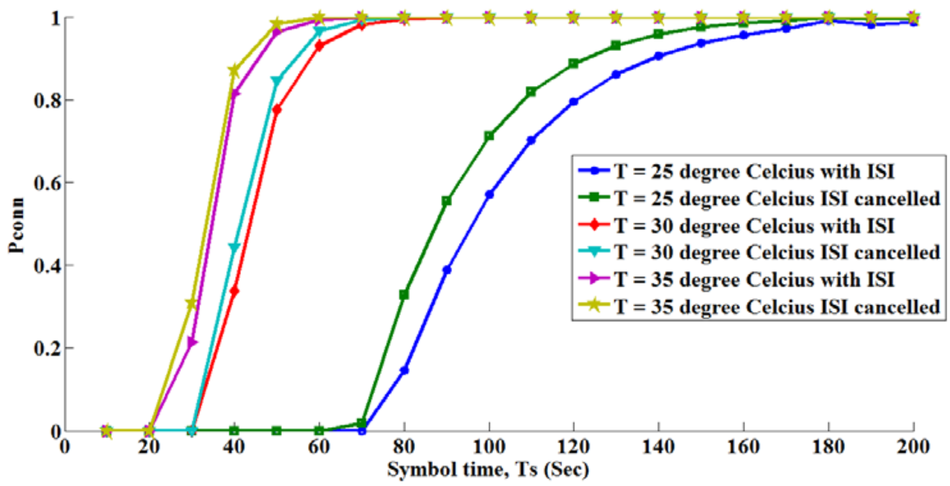

Fig. 4. P_{conn} values at various temperature with and without enhanced memory-1 cancellation scheme (X =0, N =1000)

Again, P_{conn} seems to improve with cancellation of ISI. With increase in X, performance of enhanced Memory-1 cancellation scheme increases. At X = 0.7, 28% improvement in P_{conn} is observed. As X speed of molecular transport reduces, resulting in slow down of P_{conn}. Still, T_s can be reduced up to 140 seconds for getting maximum P_{conn}.

At the outset, it is observed that enhanced Memory-1 cancellation method improved P_{conn} for various environmental conditions.

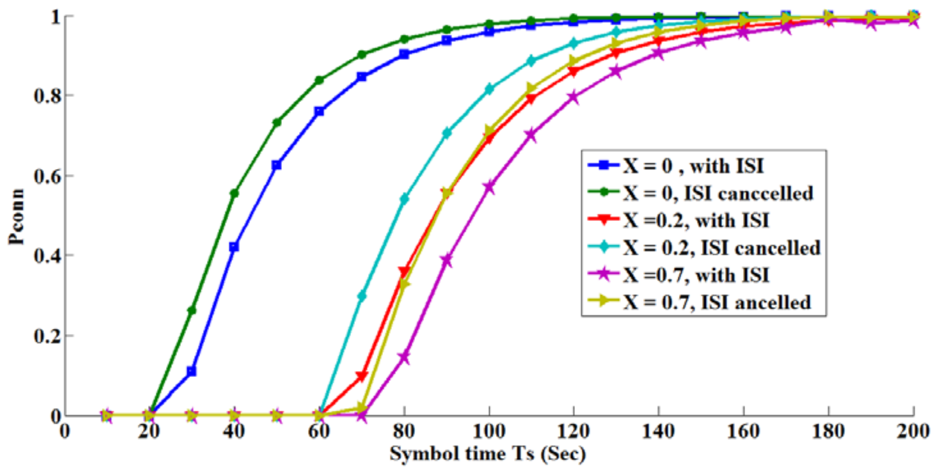

Fig. 5. P_{conn} values at various X with and without enhanced memory-1 cancellation scheme (T =25°C, N =1000)

5. Conclusion

This paper has proposed an enhancement over original Memory-1 ISI cancellation scheme for diffusion based MC to make it adaptable to variable channel conditions. This work characterizes channel conditions by a parameter λ, which is a function of diffusion coefficient, which in turn depends on environmental parameters as temperature and concentration of physical obstructions in the channel.

A maximum likelihood estimator for λ is developed and tested for performance. It is observed that with increasing N (number of molecules used in estimation), Mean Squared Error (MSE) reduces. Also for given simulation parameters, CRLB presents a lower bound on MSE values.

This estimator is further used to augment original Memory-1 ISI mitigator, which makes ISI determination process adaptive to the environmental changes, augments amount of ISI molecules in the reception. Simulations demonstrate that connectivity of MC based nano scale networks improves by using enhanced Memory-1 cancellation method P_{conn} under various environmental conditions. Maximum improvement of 28% in P_{conn} is observed at 25°C and X =0.7. This work can be further improved by computing energy requirements for implementation of enhanced Memory-1 ISI cancellation scheme.

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Prachi Raut received B.E. and M.E. degrees in Electronics Engineering from Mumbai University in 2001 and 2008 respectively. She is working as Associate Professor at the St. Francis Institute of Technology, Mumbai, India. Currently, she is pursuing PhD under guidance of Dr. Nisha Sarwade at the Veermata Jijabai Technological Institute, Mumbai, India. Her areas of specialization include Nano scale networking, Wireless communication and Signal Processing.

Dr. Nisha Sarwade received B.E. degree in Electronics Engineering from Jiwaji University, Gwalior and M.E. (Solid State Electronics) and PhD (Electronics Engineering) from University of Roorkee. She was working as a lecturer at the University of Roorkee during 1983-1987. She has worked at the Veermata Jijabai Technological Institute, Mumbai, India from 1988 to 2015 on various positions. She retired from the VJTI in July 2015 as Associate Professor. However, she continues to guide doctoral students. Her research interests include Nano Electronics with emphasis on CNT, Compound semiconductors, High-k dielectrics and flash memories and Microwave circuit design.