BT_511: Molecular Communications: Model Based and Data Driven Receiver Design and Optimization. ①

⇒ System Model.

3D unbounded diffusion channel model without flow.

The transmitter is located at $a = (0, 0, 0)$ and the receiver at $b = (b_x, b_y, b_z)$

→ The hitting rate of each info. particle can be given as

$$f_{hit}^{3D}(t) = \frac{r(d-r)}{d\sqrt{4\pi D t^3}} e^{-\frac{(d-r)^2}{4Dt}} \quad \text{---} \quad (1)$$

Here $||a-b|| = d$, distance between the transmitter and the center of the receiver

r is the radius of the receiver.

→ On-Off Keying modulation scheme is used.

The hitting probability of an absorbing receiver, to absorb one particle after t seconds

$$P_{hit}(t) = \int_0^t f_{hit}(t)\,dt \quad \text{---} \quad (2)$$

From (1) and (2)

$$P_{hit}(t) = \int_0^t f_{hit}(t)\,dt = \frac{r}{d}\,\mathrm{erfc}\frac{(d-r)}{\sqrt{4Dt}}$$

⇒ System Model

Assumptions :-

→ Temperature is constant
→ Viscosity η remains same
→ Diffusion Coefficient is constant.

$$I_i = \lambda_0 T + \sum_{j=1}^{\infty} s_{i-j} C_j$$

Here I_i represents the sum of ISI (Inter Symbol Interference) and the background noise.

λ_0 is the background noise power per unit time.

The Probability of receiving r_i information particles is

$$P(r_i \mid I_i + s_i C_0) = \frac{e^{-(I_i + s_i C_0)} (I_i + s_i C_0)^{r_i}}{r_i!}$$

L is the length of the Poisson channel.

→ The SNR ratio is defined as

$$SNR = 10 \log_{10} \frac{C_0}{2\lambda_0 T}$$

For a certain value of SNR, the number of released particles, NTx

$$NT_x = 2\lambda_0 T 10^{\frac{SNR}{10}} / P_0.$$

⇒ Optimal Zero Bit Memory Receiver.

I — represents the demodulation threshold.
$\bar{s_i}$ — estimate of s_i at time-slot i.

The demodulation rule can be formulated as.

$$\bar{s_i} = \begin{cases} 0, & x_i \leq I \\ 1, & x_i > I \end{cases}$$

The traditional approach to determine the threshold I is obtained by imposing

$$P(x_i = I | s_i = 0) = P(x_i = I | s_i = 1)$$

The probability of receiving x_i particles conditioned upon s_i is

$$P_{app}(x_i | s_i) = \frac{e^{-\lambda|s_i} (\lambda|s_i)^{x_i}}{x_i!}$$

where $\lambda|s_i = C_0 s_i + \frac{\sum_{j=1}^{L} C_j + \lambda_0 T}{2}$

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By the equality $P_{app}(r_i|s_i=0) = P_{app}(r_i|s_i=1)$

$$T = \frac{c_0}{\ln\left(1+\frac{c_0}{\sum_{i=1}^{L} c_i/2+\lambda_0 T}\right)}$$

⇒ The threshold which minimizes the BER of the zero-bit memory receiver is

$$(T^*, P_e^*) = \arg_T \min P_e(t)$$

$P_e(t)$ is the BER as a function of T

$$P_e(t) = \frac{1}{2^L} \sum_{s_i=1} P_e(s_{i-1}, t)$$

$$P_e(s_{i-1}, T) = \frac{1}{2}\Big[Q\big(\lambda_0 T + \sum_{j=1}^{L} s_{i-j} c_j, \lceil T \rceil\big) + 1 - Q\big(\lambda_0 T + \sum_{j=1}^{L} s_{i-j} c_j + c_0, \lceil T \rceil\big)\Big]$$

where $Q(\lambda, n) = \sum_{k=n}^{\infty} \frac{e^{-\lambda}\lambda^k}{k!}$ is the incomplete Gamma function and $Q(\lambda, 0) = 1$.

⇒ Optimal One Bit Memory Receiver

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In order to optimize the performance of a one-bit memory receiver, it has a prior information than the zero bit memory receiver.

$$\bar{s}_i = \begin{cases} 0, & r_i \leq T|s_{i-1} \\ 1, & r_i > T|s_{i-1} \end{cases}$$

$T|s_{i-1}$ is the threshold for the i^{th} symbol when the previously transmitted symbol is s_{i-1}

⇒ The optimal detection threshold of the one-bit memory receiver can be given as-

$$T^*|s_{i-1} = \arg_T \min P_e(T, s_{i-1})$$

the BER can be given as-

$$P_e(T, s_{i-1}) = \frac{1}{2^{L-1}} \sum_{s_{i-2}, \ldots, s_{i-L}} P_e(s_{i-1}, T)$$

⇒ Optimal K-Bit Memory Receiver.

This setup yields the optimal performance but needs more a priori information on the previously detected bit which increases the complexity.

The optimal detection threshold of the K-bit memory receiver is

$$I^*\big|_{s_{i-1},\dots,s_{i-k}} = \arg\min_{I} P_e(I, s_{i-1},\dots,s_{i-k})$$

where BER is as follows

$$P_e(I, s_{i-1},\dots,s_{i-k}) = \frac{1}{2^{L-k}} \sum_{s_{i-k+1}\dots s_{i-L}} P_e(s_{i-L}, I)$$

☆ Data Driven Receiver Design.

⇒ Zero Bit Memory Receiver.

An ANN based zero-bit memory demodulator is a system whose input consists of the received information particles r_i at the ith time slot and the outputs are the probabilities that the transmitted bit is 0 and 1.

ie $P_i(s_i = 0 \mid r_i)$ and $P_i(s_i = 1 \mid r_i)$

$$P_i(s_i = 1 \mid r_i) + P_i(s_i = 0 \mid r_i) = 1.$$

Based on the input, the ANN demodulates the received data as

$$\hat{s_i} = \begin{cases} 0, & P_i \leq 0.5 \\ 1, & P_i > 0.5. \end{cases}$$

where the threeshold 0.5 accounts for the fac that the bits are equiprobable

⇒ One-Bit Memory Receiver:

In this type, the input of the ANN is not just the number of received particles at the ith time slot, r_i but also the estimated symbol at the (i-1)th time slot $\hat{s}_{i-1}$.

$$\hat{s_i} = \begin{cases} 0, & P(s_i = 1 \mid r_i, \hat{s}_{i-1}) \leq 0.5 \\ 1, & P(s_i = 1 \mid r_i, \hat{s}_{i-1}) > 0.5 \end{cases}$$

⇒ K-Bit Memory Receiver.

By using the same method as the one-bit memory receiver, the decision rule can be formulated as.

$$\hat{s_i} = \begin{cases} 0, & P(s_i = 1 \mid r_i, \hat{s}_{i-1}, \ldots, \hat{s}_{i-k}) \leq 0.5 \\ 1, & P(s_i = 1 \mid r_i, s_{i-1}, \ldots, \hat{s}_{i-k}) > 0.5 \end{cases}$$