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Effect of receiver shape and volume on the Alzheimer disease for molecular communication via diffusion

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Abstract: Nano-devices are featured to communicate via molecular interaction, the so-called molecular communication (MC). In MC systems, the information is carried by molecules where the amount of molecules constitutes the level of the signal. In this study, an MC-based system was analysed with different receiver topology and related parameters, such as size, shape, and orientation of receptors on the receiver. Also in the concept of nano-medicine, the effect of amyloid-beta (A_β), which is believed as the main cause of Alzheimer disease, on the successful reception ratio of molecules with the proposed receiver models was investigated. It was demonstrated that the cubic receiver model is superior to sphere one in terms of the correct reception ratio of the molecular signal. A cubic model where its edge (not rotated around the centre) is placed across the transmitter demonstrated a better performance in reducing the effect of A_β as compared to the sphere model while a cubic model where its corner (rotated around the centre) is placed across the transmitter demonstrated a worse performance than the spherical model. From this expression, it may be concluded that with the adjustment of topological system parameters the probability of successful reception ratio in MC may be possible.

1 Introduction

In recent years, numerous studies have been conducted for establishing communication of nano-devices mainly based on the theory of molecular transport through fluid media, the so-called molecular communication (MC). In such a communication system, beside the transmitter (Tx) and the receiver (Rx) design play an important role in the performance enhancement of the system in terms of the ratio of the received molecules that are transmitted through the diffusive fluid media [1–4]. In addition to receiver models, molecular antenna models have also been proposed to improve the reception ratio. Chemical transceivers have been considered for many areas, such as bio-medical, environmental monitoring, and defence systems [3]. In these transceiver models, usually, the chemical receptors have been considered as antennas because of the similarity of their structure to the digital antennas. Receptors are found on the receiver surface of almost all biological cells, which are used for receiving proteins, nutrient, or other substances.

In the literature, MC systems principally consist of a point transmitter, a diffusive medium that is characterised with a channel transfer function, and a fully absorbing spherical receiver. In these systems, the attenuation and the propagation delay of the signal are analysed in one- and three-dimensional (i.e. 1D and 3D) environments [4, 5]. The received molecular signal is defined by the transmitted molecules that reach the receptor sites on the receiver surface. A critical goal of MC studies has been to improve the reception of the molecules reaching the receiver surface.

Towards finding a way for increasing the reception ratio of molecules, the effect of size and density of receptors has been investigated for a point transmitter and a spherical receiver with surface receptors in [6]. The absorption ratio of the receiver for the considered topology has been analytically calculated and the performance analysis of such a system has been done for the reception probability while varying the number and size of receptors. It has been found that when the total receptor deployment area remained the same, the success ratio of reception for small-sized receptors becomes higher as compared to larger-sized receptors. In our study, we further this line of research by investigating the effect of a number of receptors and also receiver's size (keeping the receptor area same) on the molecular reception ratio for a spherical receiver model, and analyse the results that show that higher volumes yield worse signal quality.

Einolghozati *et al.* [7] have proposed a receiver with ligand receptors, which include bins for molecules to interpose and start signalling inside the cell. In this pioneering study, the receiver of the system has been considered to possess a large number of binding seats and the molecular concentration over each of these seats has been calculated with a Markov chain model. The total reception ratio of a receiver has been estimated by averaging the concentrations over all binding seats [7]. In order to test the system for achieving higher reception ratios, the transmitter released molecules at either low or high concentrations to achieve 'low' and 'high' signal levels similar to binary generators. As a result, the authors are obtained the capacity of ligand-receptor, which was increased for a higher number of receptors. In such models, a medium ratio of concentrations is avoided at the transmitter side to not to cause any ambiguity as neither 'low' nor 'high'.

To increase the ratio of reception, a novel architecture of antenna models, which are mainly composed of a spherical receiver and supported with a totally reflective spherical or cylindrical shell oriented over or around the receiver, has been introduced in [8]. This is done to trap or confine the molecules, which are run off from receptors. In our study, we propose the use of cubic receivers instead of the conventional spherical receivers used in the literature, following the idea of increasing the surface area to provide more spreading possibility of the receptors. Through Monte Carlo simulations, we evaluate the effect of receiver shape on the reception ratio, which suggests better receiver possibilities in terms of reception probability. Cubic membranes symbolise curved, 3D nano-periodic structures that resemble to triply periodic minimal surfaces. Although they have been observed in numerous cell types and under different conditions, mostly in stressed, diseased, or virally infected cells, knowledge about the formation and function of non-lamellar, cubic structures in biological systems is uncommon. Cubic membranes can be used for gene transfection in the benign medium [9]. In [10], the morphology of mitochondrial cristae can be modified

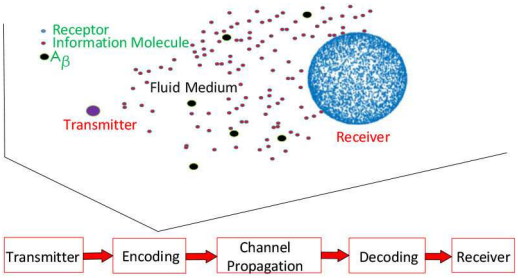

Fig. 1 *General MC model with a spherical receiver and a point transmitter*

under a range of physiological and pathological conditions, particularly stressed conditions [11]. Transmission electron microscopy (TEM) studies reveal that mitochondrial cristae in amoeba Chaos undergo conformational changes under starvation-stress conditions, leading to the formation of unambiguous cubic membrane morphology [12, 13]. Cubic membranes thus may offer a new, potentially benign medium for gene transfection.

A_β protein exists in both intra and extracellular regions in the central nervous system with different construction levels and plays distinct roles ranging from regulation of synaptic function and memory formation to memory loss and neuronal cell death [14]. The excess accumulation of A_β peptide plaques on the cell membrane as well as in the inter-neuronal synaptic cleft is known to affect the nervous system, particularly the synaptic mechanism, and hence degrades the quality of information exchange between neurons [15, 16]. It is known that amount of A_β that is more than just the adequate amount affects the inter-neuron communication and possibly causes Alzheimer disease. Hence, in our study, we also evaluate the effect of A_β on the reception ratio by introducing A_β peptide at different amounts into the inter-neuron environment. We have placed spherical components into the diffusion environment and the proposed model has been analysed by changing the ratio of these components.

The remaining of the paper is organised as follows. In Section 2, we explain the proposed system models. In Section 3, the proposed system model is analysed with results. Finally, Section 4 concludes the paper.

2 System model

2.1 Diffusion model

The model used in this study consists of a point transmitter, a diffusive channel and a spherical receiver, the receptors of which are placed on its surface (Fig. 1). The whole system is considered as if it is in an aqueous medium. The centre of the receiver is placed at the origin (0, 0, 0) of the model-space and the transmitter is placed at a distance d from the receiver surface. As the molecules are released into the fluid medium by the transmitter, they diffuse via Brownian motion. Hence, the molecules arrive at the receiver in a probabilistic manner that depends on the system parameters. The receptors possessing a spherical shape with radius r_s are located at the surface of the receiver to absorb molecules. Systematically, if a molecule collides with one of the n receptors deployed at the receiver surface, the molecule is absorbed by the receiver and in this way the receiver receives the information. If it hits the surface of the receiver without contact of any receptors, the molecule bounces back as also defined in [6].

The diffusion process is simulated via a Monte Carlo method for a free diffusion molecular channel in a 3D environment. The displacement of molecules in each dimension follows a Gaussian distribution, the discretisation of which is done through Δt-length time steps. Therefore, the diffusion process of molecules is simulated by adding the displacement vector to the present location vector for determining the next position of a molecule as follows:

$$\begin{aligned} \boldsymbol{r}[k] &= \boldsymbol{r}[k-1] + \Delta\boldsymbol{r} \\ \Delta\boldsymbol{r} &= (\Delta r_1,\ \Delta r_2,\ \Delta r_3) \\ \Delta r_i &\sim N(0, 2D\Delta t) \quad \forall(i) \in \{1, 2, 3\} \end{aligned} \tag{1}$$

where $\boldsymbol{r}[k]$ is the location vector of a molecule at the kth time instance, r_i represents the ith component of the location vector $\boldsymbol{r}$, Δt is the discrete simulation time step, D is the diffusion coefficient, and $N(\mu, \sigma^2)$ is the Gaussian random variable with mean μ and variance σ^2.

For a fully absorbing spherical receiver model, the cumulative number of received molecules is derived analytically as in (2). For a molecule in the transition process, the absorption probability by the receiver until the time t is given as

$$F_{\text{success}}(t) = \frac{r_r}{d + r_r}\text{erfc}\left(\frac{d}{\sqrt{4Dt}}\right), \tag{2}$$

where r_r stands for the radius of the receiver, t is the duration after the release of the molecule, d is the distance between the transmitter and the closest point on the surface of the receiver and finally, $\text{erfc}(\cdot)$ is the complementary error function [4]. Biologically, if a messenger molecule hits the body of the receiver or the receptor, this molecule is received and removed from the environment. In this study, it is considered that the hitting molecule cannot move after that point and constitutes the signal just once. This is known as the first passage or the hitting process. The probability of this first hitting process where diffusing particles first reaches a specified site at a specified time in 3D environments is given in (2). So, the channel coefficients can be found by utilising (2) as

$$h_k = F_{\text{success}}((k+1)t_s) - F_{\text{success}}(kt_s), \quad k = 0, 1, 2, \ldots \tag{3}$$

where t_s is the duration of a symbol slot. For an asymmetric complex topology, Monte Carlo simulations are performed to obtain the channel coefficients, which determine the number of successfully received molecules within a successive symbol slot. Knowing $F_{\text{success}}(t)$ is one of the essential steps for evaluating the performance of the system in the MC studies. If $F_{\text{success}}(t)$ is known or can be obtained via simulations then the number of received molecules at the ith symbol time slot ($N^{\text{Rx}}[i]$) can be formulated as follows:

$$\begin{aligned} N^{\text{Rx}}[i] &= \sum_{k=1}^{i} N_k^{\text{Rx}}[i] \\ N_k^{\text{Rx}}[i] &\sim \mathcal{B}\left(N^{\text{Tx}}[k],\ h_{i-k}\right) \end{aligned} \tag{4}$$

where $N_k^{\text{Rx}}[i]$ denotes the number of received molecules during the ith symbol slot, which is emitted at the start of the kth symbol slot, $N^{\text{Tx}}[k]$ represents the number of emitted molecules at the start of the kth symbol slot, and $\mathcal{B}(n, p)$ denotes the binomial random variable with n trials and the success probability p. In this study, we obtain $F_{\text{success}}(t)$ via simulations and analyse the received molecular signal in terms of estimation of molecular reception probability and interference molecules.

2.2 Antenna shapes

In digital communication systems, particular antenna models are tested to increase the ratio of receiving correct information. In a similar notion, in an MC system, the information molecules need to be received adequately, which can possibly be optimised by particular receiver shapes. Receptors that are naturally found in almost all biological cells are of important elements functioning during cell interactions. In MC systems, receptors have to be placed on the receiver at appropriate positions with a density that would be enough to receive the molecular signal efficiently. It should be noted that the parameters of the receptor deployment affect the production cost of nano-scale devices [6]. In addition to

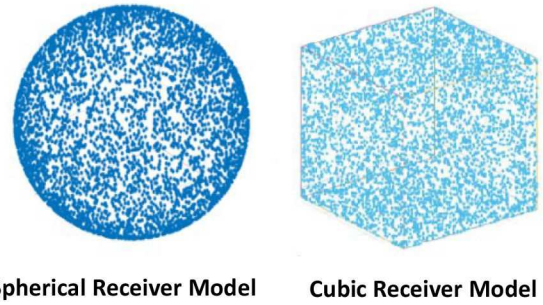

Fig. 2 *MC model with sphere and cube receivers in which the whole surface is uniformly covered with 1800 receptors. Blue dots are the receptor points on the receiver node*

receptor placement on the receiver, the shape of the receiver also affects the molecule reception probability. In this study, in addition to the spherical receiver model, a cubic receiver model, as shown in Fig. 2, is also studied for understanding the effect of the receiver's topology on the molecular reception ratio. While examining different receiver shapes the volume of the receiver is kept constant for consistency.

2.3 Effect of A_β on the receiver models

For simulating Alzheimer disease in the MC framework, some spherical blockading particles – that is mimicking A_β peptides – were randomly situated within the synaptic cleft, as shown in Fig. 1. Here, while the information-carrying molecules are transmitted through the channel, A_β peptide behaves as the disturbance since they trap or block the information molecules. If a molecule encounters the blockades, then it is excluded from the process of molecular transmission. In this study, in order to increase the ratio of molecular reception in the proposed MC system with induced A_β, both spherical and cubical receiver models were tested in terms of successful reception ratios. The ratio of A_β with respect to a number of emitted molecules is considered to find the effect of A_β on the reception ratio of molecules. Because the number of A_β cannot be used directly to analyse the effect of A_β on the channel. The ratio of A_β is calculated as below to find the successful reception ratios

$$\text{Ratio of } A_\beta = \frac{N^{A_\beta}[0]}{N^{\text{Tx}}[0]}, \tag{5}$$

where $N^{\text{Tx}}[0]$ is the number of emitted molecules and $N^{A_\beta}[0]$ is the number of A_β particles in the medium at $t = 0$. In this study, the aim is to examine whether the effect of A_β on the precision of MC could be reduced by the use of different antenna topologies or not.

3 Results and discussion

In this study, the effect of receptor size, receiver volume, and the amount of A_β peptide on the molecular reception ratio is estimated by the absorption probability, $F_{\text{success}}(t)$. The estimation of h_0, i.e. the ratio of received molecules in the duration of the first symbol slot is given as

$$\widehat{h_0} = \frac{N^{\text{Rx}}[0]}{N^{\text{Tx}}[0]} \tag{6}$$

where $\widehat{h_0}$ is an estimate of actual h_0 and $N^{\text{Rx}}[0]$ is the number of received molecules for the first symbol slot (i.e. between $t = 0$ and $t = t_s$).

Another performance metric is the signal-to-interference-molecules ratio (SIR) and it is calculated as

$$\text{SIR}_{t_s} = \frac{\widehat{h_0}}{\sum_{k \in \{1,\ldots,K_{\text{end}}\}} \widehat{h_k}} \tag{7}$$

where SIR_{t_s} denotes the ratio of desired signal molecules to interference molecules when the symbol slot is t_s and K_{end} denotes the last symbol index taken into account. In (7), $\hat{h}_0$ represents the probability of received molecules successfully that are emitted at the start of the current symbol slot (i.e. the molecules that are forming the intended signal) and $\hat{h}_i$ refers to the number of received molecules that are emitted at the start of the ith-previous symbol slot (i.e. the molecules that are causing the inter-symbol interference (ISI)). Please note that the channel coefficients are showing the effect of the emitted signal during the current symbol slot by $\hat{h}_0$ and during the subsequent symbol slots by $\hat{h}_i$, where $i>0$. Therefore, (7) formulation just divides the number of received molecules for intended signal by the interference molecules (i.e. the remaining molecules from the previous emissions/symbols). Including $\hat{h}_0$ as an interference can only happen if there is a multi-user interference, which we kept out of scope for this study. In brief, the performance evaluations are done in terms of $F_{\text{success}}(t)$, $\hat{h}_0$ (see (3) and (6)), and SIR (see (7)).

3.1 Spherical receiver

The designed diffusion-based MC system was examined in terms of the estimated reception ratio, $\widehat{h_0}$, while using the spherical receiver model. The total area of receptors on the receiver surface is kept constant in all evaluations for fairness purposes. The receptors are distributed uniformly random on the surface of the receiver.

In this section, firstly, the effect of receiver volume on $\widehat{h_0}$ and SIR is examined for a spherical receiver model, while keeping the number of receptors fixed. The effect of the receiver volume for a spherical receiver is given in Figs. 3 and 4. As shown in these figures, the highest $\widehat{h_0}$ and SIR were obtained with the smallest receiver volume, whilst the number of receptors was kept constant. Please note that the receiver volume cannot be smaller than the volume satisfying the required surface area for the receptors.

To figure out the reason for a higher $\widehat{h_0}$ and SIR for a smaller volume, the distances between the emission point and the receptor centres on the receiver are measured. In Fig. 5, the distance histogram is depicted. When the receiver volume is increased, the mean distance to a random receptor increases, which results in more latency and interference. The mean distance, where the smaller mean distance implies a better efficiency in reception ratio, between transmitter and centre of all receptors on the spherical receiver is calculated as 8.22, 10.75, and 12.35 μm for receiver volume of 100, 500, and 1000 μm^3, respectively. Similarly, the mean distance between the transmitter and the receptors on the cubic receiver is calculated as 7.7382, 9.9499, and 11.4117 μm for the same receiver volumes, respectively.

3.2 Cubical and spherical receivers

From the receiver modelling perspective, a model which uses a purely reflecting shell placed at a suitable distance and/or orientation and/or volume around the receiver surface is similar to a satellite dish that increases the signal reception probability.

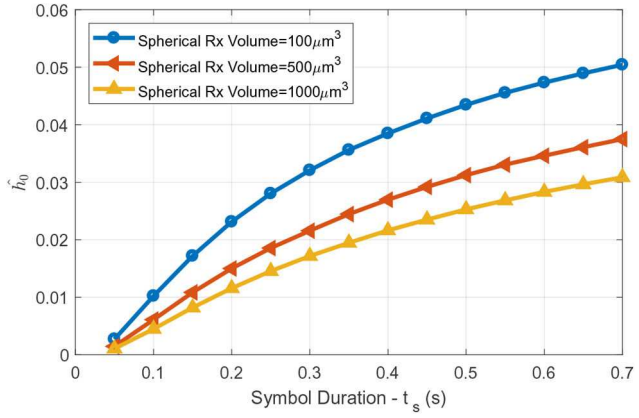

Fig. 3 *Symbol duration versus $\hat{h}_0$ values of a spherical receiver for different volume of receiver ($r_s = 0.02\,\mu$m, $d = 5\,\mu$m, $N^{\mathrm{Tx}}[0] = 20,000$ molecules, $D = 79.4\,\mu\mathrm{m}^2/\mathrm{s}$, $N_{\mathrm{receptor}} = 1800$, and the replication count is 100)*

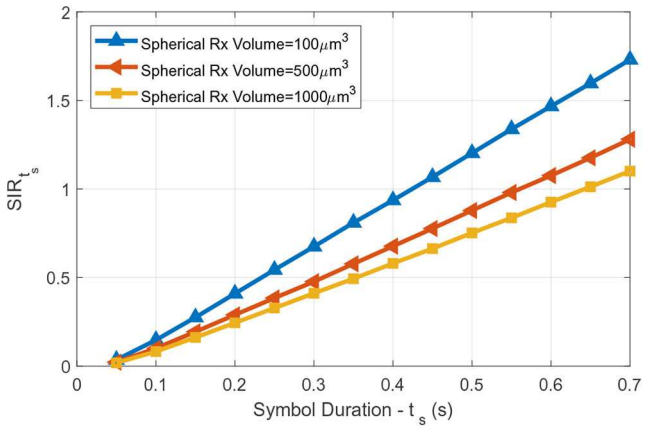

Fig. 4 *Symbol duration versus SIR_{t_s} values of a spherical receiver for different volume of receiver ($r_s = 0.02\,\mu$m, $d = 5\,\mu$m, $N^{\mathrm{Tx}}[0] = 20,000$ molecules, $D = 79.4\,\mu\mathrm{m}^2/\mathrm{s}$, $N_{\mathrm{receptor}} = 1800$, and the replication count is 100)*

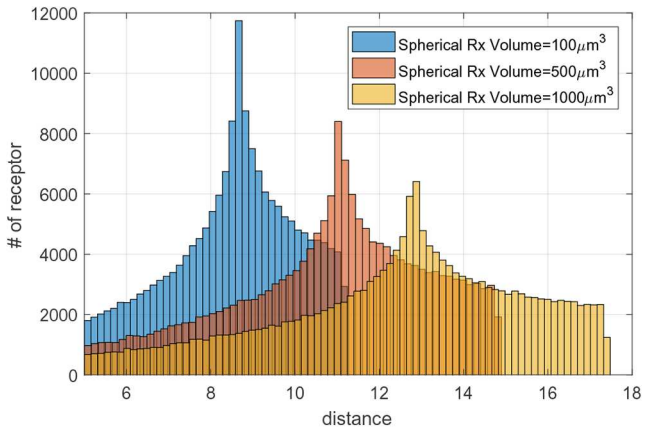

Fig. 5 *Distance histogram for receptor locations with a fixed number of receptors ($r_s = 0.02\,\mu$m, $d = 5\,\mu$m, $N^{\mathrm{Tx}}[0] = 20,000$ molecules, $D = 79.4\,\mu\mathrm{m}^2/\mathrm{s}$, $N_{\mathrm{receptor}} = 1800$, and the replication count is 100)*

Following a similar idea, in this study, a cubic receiver model is considered as a substitute to the spherical receiver used in the literature. In our simulation, we considered the cube receiver as six different plates and to find which molecules are inside of it or not; we compared the coordinates of molecules with the boundaries of the cube. If the coordinates of a transmitted molecule reside inside the cube generated by these plates, then it is considered as received.

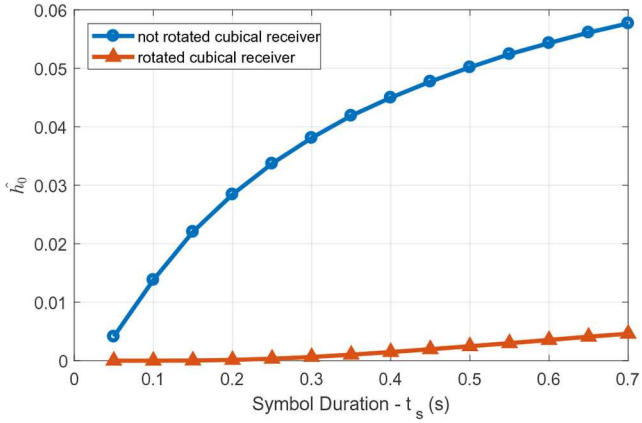

Fig. 6 *Symbol duration versus $\hat{h}_0$ values of a cubical receiver for rotating and not rotating it around the centre ($r_s = 0.02\,\mu$m, $d = 5\,\mu$m, $N^{\mathrm{Tx}}[0] = 20,000$ molecules, $D = 79.4\,\mu\mathrm{m}^2/\mathrm{s}$, $N_{\mathrm{receptor}} = 1800$, and the replication count is 100)*

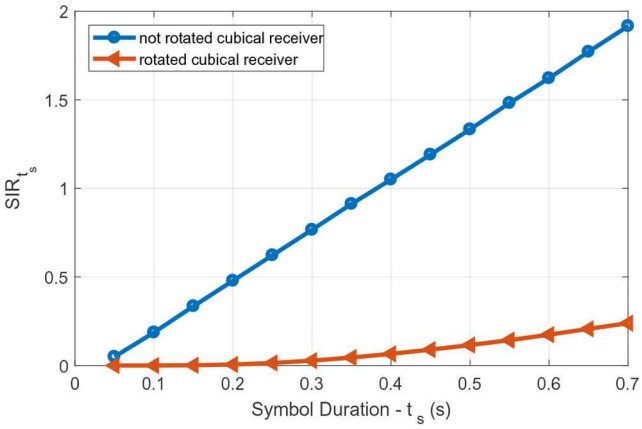

Fig. 7 *Symbol duration versus SIR_{t_s} values of a cubical receiver for rotating and not rotating it around the centre ($r_s = 0.02\,\mu$m, $d = 5\,\mu$m, $N^{\mathrm{Tx}}[0] = 20,000$ molecules, $D = 79.4\,\mu\mathrm{m}^2/\mathrm{s}$, $N_{\mathrm{receptor}} = 1800$, and the replication count is 100)*

In this study, firstly the proposed cubic receiver model is analysed for keeping the distance between the centre of the receiver and the transmitter constant. However, other analysis in this study considered by keeping the distance between the transmitter and the closest point on the surface of the receiver. Also, the cubic receiver model is considered for rotated (corner of the cubic model placed across the transmitter) and not rotated (edge of the cubic model placed across the transmitter) conditions. Because the orientation of the cubic receiver model around the centre affects the probability of received molecules at the receiver, as shown in Fig. 6 ($\widehat{h_0}$) and Fig. 7 (SIR_{t_s}). It is obviously seen from the figures that $\widehat{h_0}$ and SIR_{t_s} values decrease sharply with rotating the cube around the centre. We think that this is because of the mean distance between the receptors and transmitter, as shown in Fig. 5 (distance histogram). It should also be noted that the cubic receiver model is better than the spherical model unless it is rotated.

In Fig. 8 ($\widehat{h_0}$) and Fig. 9 (SIR_{t_s}), the most efficient receiver model was found for the cubic model with $500\,\mu\mathrm{m}^3$, while the worst case was for a spherical model with $100\,\mu\mathrm{m}^3$. It is clearly seen that values of $\widehat{h_0}$ and SIR are higher for a bigger volume of the receiver when the distance between the centre of the transmitter and the receiver is kept constant because if the volume of the receiver is increased, the distance between the transmitter and the receptor centres will decrease and finally, the reception ratio increase and interference decrease because of the shorter distance. The cubic receiver model shows better performance, even distance

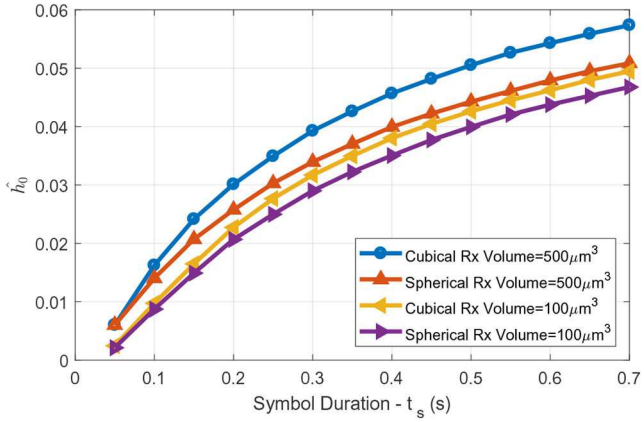

Fig. 8 $\widehat{h_0}$ *plot of spherical and cubic receivers for different volume of receivers* ($r_s = 0.02\,\mu$m, $N_{\text{receptor}} = 1800$, $N^{\text{Tx}}[0] = 20,000$ *molecules,* $D = 79.4\,\mu\text{m}^2/\text{s}$, *the distance between the centre of the transmitter and receiver is kept constant, and the replication count = 100)*

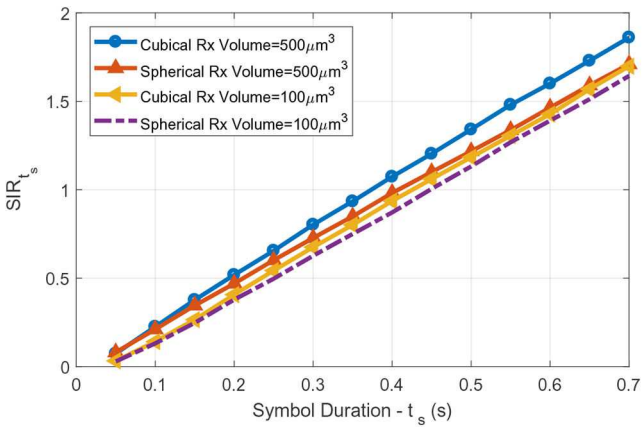

Fig. 9 SIR_{t_s} *plot of the spherical and cubic receivers for different volume of receivers* ($r_s = 0.02\,\mu$m, $N_{\text{receptor}} = 1800$, $N^{\text{Tx}}[0] = 20,000$ *molecules,* $D = 79.4\,\mu\text{m}^2/\text{s}$, *the distance between the centre of transmitter and receiver is kept constant, and the replication count = 100)*

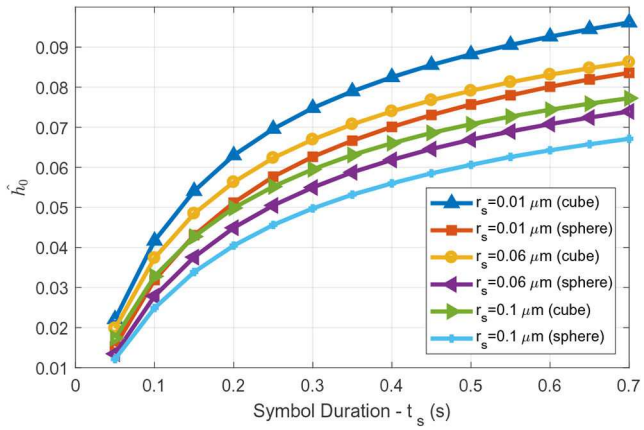

Fig. 10 $\widehat{h_0}$ *plot of spherical and cubic receivers for the different radius of receptors (Rx volume* $= 125\,\mu\text{m}^3$, $N^{\text{Tx}}[0] = 20,000$ *molecules,* $D = 79.4\,\mu\text{m}^2/\text{s}$, $d = 5\,\mu$m, *and the replication count = 100)*

between the centre of the receiver and the transmitter constant. When the radius of the receptor is changed, the following analysis results are obtained. In Fig. 10 $\widehat{h_0}$ and in Fig. 11 SIR_{t_s} results are shown for the spherical and cubic receiver models with equal volumes for the different radius of receptors. The most efficient receiver model was found with $r_s = 0.01\,\mu$m ($N_{\text{receptor}} = 7200$) for the cubic model, while the worst case was for $r_s = 0.1\,\mu$m

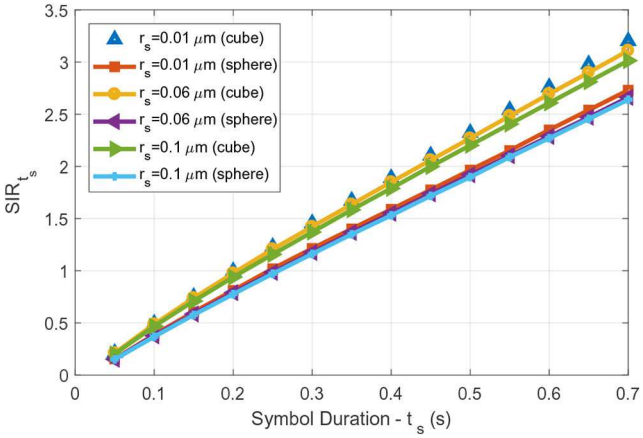

Fig. 11 SIR_{t_s} *plot of spherical and cubic receivers for the different radius of receptors (Rx volume* $= 125\,\mu\text{m}^3$, $N^{\text{Tx}}[0] = 20,000$ *molecules,* $D = 79.4\,\mu\text{m}^2/\text{s}$, $d = 5\,\mu$m, *and the replication count = 100)*

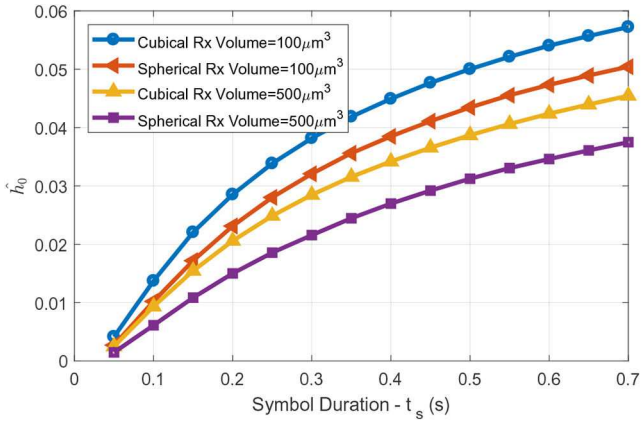

Fig. 12 $\widehat{h_0}$ *plot of spherical and cubic receivers for different volume of receivers* ($r_s = 0.02\,\mu$m, $N_{\text{receptor}} = 1800$, $N^{\text{Tx}}[0] = 20,000$ *molecules,* $D = 79.4\,\mu\text{m}^2/\text{s}$, $d = 5\,\mu$m, *and the replication count = 100)*

($N_{\text{receptor}} = 72$) for the spherical model. From this result, we can deduce that the smaller-sized receptors result in higher values for $\widehat{h_0}$, which implies that the higher number of receptors on the receiver surface contributes positively to the reception ratio, which therefore enhances the communication quality in MC system. This observation is highly in line with the data presented in [6]. This is due to the increase in the homogeneity of deployed receptors with the replacement of small-sized receptors (i.e. if you consider an extreme case and assume a single receptor with the same area, then the only absorbent part will be the receptor area and the homogeneity will be degraded). Therefore, it could be said that the molecular reception ratio is correlated with the number of receptors per unit surface area. In addition to receptor analysis, we further analyse the shape and volume of the receiver for a fixed value of the distance between the transmitter and the closest point on the surface of the receiver in this study. As shown in Figs. 12 and 13, the cubic receiver has higher SIR_{t_s} and $\widehat{h_0}$, which shows that a cubic receiver would exhibit a better performance if used as a receiver in MC systems. The reason is that for a cube receiver with the same volume, the average transmitter–receptor distance is less compared to the sphere as illustrated in the previous subsection. The distance between the centre of the transmitter and the closest point of the receiver surface is kept constant for these analyses and as a result, $\widehat{h_0}$ (Fig. 12) and SIR_{t_s} (Fig. 13) plots are obtained.

Although better results are obtained by keeping the distance between the centre of the receiver and the transmitter constants (Figs. 8 and 9), we believe that, d should be fixed to get more correct results (Figs. 12 and 13). Because in this study, the volume of the receiver is changed and molecules are considered for reception process if they are inside the receiver by hitting one of

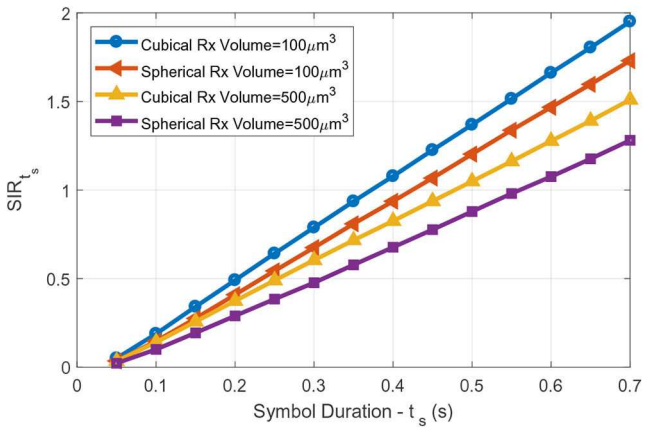

Fig. 13 SIR_{t_s} *plot of spherical and cubic receivers for different volume of receivers* ($r_s = 0.02\,\mu$m, $N_{\mathrm{receptor}} = 1800$, $N^{\mathrm{Tx}}[0] = 20,000$ *molecules,* $D = 79.4\,\mu\mathrm{m}^2/\mathrm{s}$, $d = 5\,\mu$m, *and the replication count = 100)*

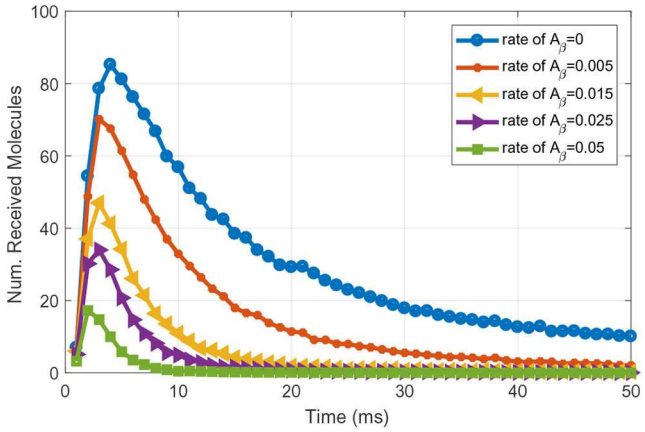

Fig. 14 *Number of received molecules for the spherical receiver* ($r_s = 0.01\,\mu$m, $N_{\mathrm{receptor}} = 7200$, $d = 3\,\mu$m, $N^{\mathrm{Tx}}[0] = 20,000$ *molecules,* $D = 79.4\,\mu\mathrm{m}^2/\mathrm{s}$ *and the number of simulations = 100)*

the receptors on the receiver. If the distance between the centre of the transmitter and receiver is kept constant, then the distance between the transmitter and surface of receiver changes and finally ratio of the received molecules changes with the volume of the receiver not the distance between the transmitter and receiver.

3.3 Effect of A_β: cube versus sphere

In this section, spherical and cubic receiver models are compared in terms of the molecular reception ratio, $\widehat{h}_0$, and SIR_{t_s} with also considering the influence of A_β molecules.

Fig. 14 shows the ratio of molecular reception with respect to A_β amount for the spherical receiver model. As shown in the figure, when the amount of A_β increases, the reception probability decreases. Similarly, the ratio of molecular reception for the cubic receiver model is shown in Fig. 15.

To analyse the cubic and spherical receivers in detail, we focus on $\widehat{h}_0$ and SIR_{t_s} for both the receiver models when there are A_β molecules in the environment. In Fig. 16, $\widehat{h}_0$, which is analogous to the amplitude of the desired signal, decrease with the increase of A_β amount as it is expected. It is also seen from the figure that the cubic receiver model is better than a spherical model for the same value of A_β with respect to $\widehat{h}_0$ value. In [17], enzymes have been used to decrease ISI in the model for molecular communication simulations. The enzymes have been placed into the diffusion environment randomly and the number of received molecules and interference were analysed by varying system parameters. Through this study, it has been observed that if the number of enzymes increased, then SIR_{t_s} increased and the number of received

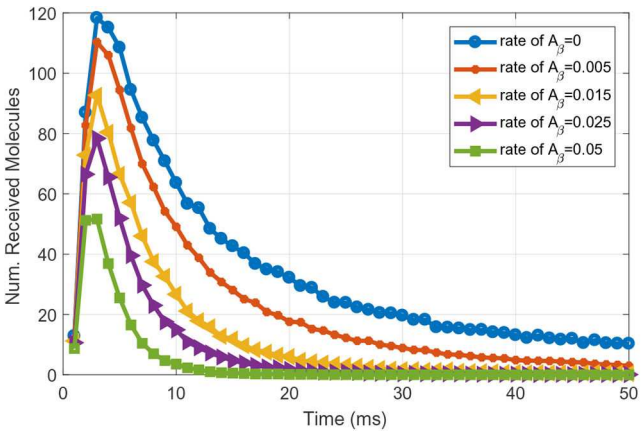

Fig. 15 *Number of received molecules for the cubic receiver* ($r_s = 0.01\,\mu$m, $N_{\mathrm{receptor}} = 7200$, $d = 3\,\mu$m, $N^{\mathrm{Tx}}[0] = 20,000$ *molecules,* $D = 79.4\,\mu\mathrm{m}^2/\mathrm{s}$ *and the number of simulations = 100)*

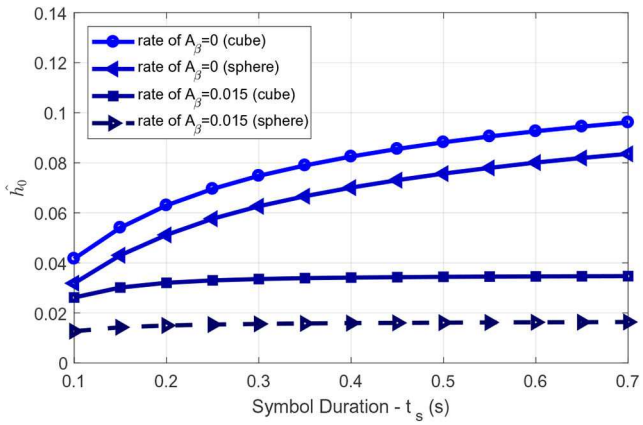

Fig. 16 $\widehat{h}_0$ *plot for spherical and cubic receivers* ($r_s = 0.01\,\mu$m, $d = 3\,\mu$m, $N^{\mathrm{Tx}}[0] = 20,000$ *molecules,* $N_{\mathrm{receptor}} = 7200$, $D = 79.4\,\mu\mathrm{m}^2/\mathrm{s}$ *and the number of simulations = 100)*

molecules decreased. In this study, the A_β has been placed into the diffusion environment like enzymes in [17], however, we aim to analyse the effect of A_β on Alzheimer diseases and finally, find that when we increase the number of A_β then the number of received molecules decrease and ISI decreases or SIR increases as expected. This is observed in the medical study of Alzheimer disease as given the last part of the introduction. Also, we showed that when we use even rate of A_β (0.015) is very high, the cubic model is better than a spherical model with respect to SIR value.

In addition to these findings, we observe that the cubic receiver model is more robust for A_β obstruction (Fig. 17). This final observation can pave the way to cope with the deteriorating effects of A_β molecules and it can suggest alternative solutions toward the treatment of Alzheimer diseases. Please note that, in all of these simulations with A_β, the number and the size of receptors are kept the same for both the receiver models.

4 Conclusion and future work

In this study, spherical and cubic receiver models were used to understand their effect on the success ratio of molecular reception in a diffusion-based MC system. The aim is to find a better MC antenna model (shape and volume of the receiver) possessing a higher ratio of molecular reception and a maximum ratio of SIR that implies a communication system with less errors. Also, the effect of A_β is analysed with both the spherical and cubic receiver models. The aim to do this was to find a better antenna or receiver models that minimise the effect of A_β. The obtained results showed that the cube receiver model has a better performance for successful molecular reception and less SIR for both with and

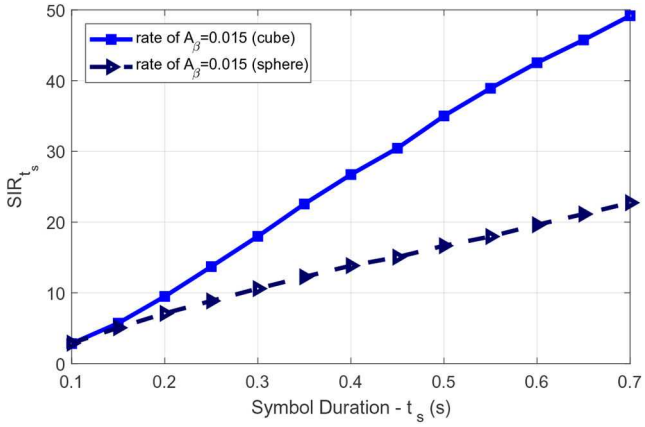

Fig. 17 SIR_{t_s} *plot for spherical and cubic receivers when there are* A_β *molecules in the environment (*$r_S = 0.01\ \mu m$, $d = 3\ \mu m$, $N^{\mathrm{Tx}}[0] = 20,000$ *molecules,* $N_{\mathrm{receptor}} = 7200$, $D = 79.4\ \mu m^2/s$ *and the number of simulations = 100)*

without A_β, compared to the spherical receiver model. Therefore, a cubic shaped receiver may be advised to be used instead of the spherical receiver in the MC system design. From these demonstrations, it was found that for both disturbance-free MC and with A_β disturbance MC systems cubic antenna shape showed a higher successful reception ratio due to possessing lower the mean distance from the transmitter. The aim with the reduction of the effect of A_β is to find out or at least seek for some solutions toward the treatment of Alzheimer diseases. For the future directions, we will concentrate on the investigation of new antenna models to increase the probability of successful molecular reception in MC system.

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