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A vertical channel model of molecular communication and its test-bed

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Abstract

The study of molecular communication is more and more prevalence, and channel model of molecular communication plays an important role in the molecular communication system. Different propagation environment and modulation techniques lead to different channel model, and most of the previous researches are mainly concentrate on the channel model in horizontal direction. However, in nature the communications between nano-machines are in short range and some of the information propagation are in the vertical direction, such as *transpiration* of plants, *biological pump* in ocean, etc. Therefore, in this paper a vertical channel model was proposed in which nano-machines communicate with each other mainly through diffusion at the vertical direction. Firstly, proposing a vertical molecular communication model, we mainly focus on the gravity, though the channel model is also affected by other main factors, such as the flow of the medium, the distance between the transmitter and the receiver, the delay or sensitivity of the transmitter and the receiver, etc. Secondly, we set up a test-bed for the vertical channel model, and verify the differences between the theoretical result and the experimental result. Finally, we get the parameters of the channel model which was proposed for the test-bed by utilizing the experimental data and the non-linear least squares method.

Keywords: Gravity, molecular communication, non-linear least squares method, test-bed, vertical channel model

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1. Introduction

Nowadays, modern telecommunication system conveys most information with electrical or electromagnetic signals. However, still there are many applications which are not convenient or appropriate for these technologies. For instance, the use of wireless communication inside networks of tunnels, pipelines, or salt water environment, etc., can be very inefficient[2, 3]. As another example, with the dimensions of the transmitter and receiver become smaller and smaller, electromagnetic communication is extremely challenging due to constrains such as the ratio of the antenna size to the wavelength of the electromagnetic signal[4].
Fifty years ago, the nobel laureate physicist Richard Feynman addressed the famous speech "There's Plenty of Room at the Bottom", which introduced the concept "nanotechnology". Recent developments in nanotechnology have enabled the manufacturing of low-power and low-cost nano-scale machines. Therefore, it is desperately needed to investigate the communication at the bottom, which comes the nano-scale communication[5]. Two main ways are proposed to implement nano-scale communication, nano-electromagnetic communication and molecular communication(MC)[6]. Molecular communication is more suitable for nano-scale communication, the evidence of which is that molecular communication is a more natural choice for biological-based nanomachines and it utilizes chemical signals as carriers of information. In molecular communication, the transmitter releases small particles such as molecules or lipid vesicles into an aqueous or gaseous medium, where the particles propagate until they arrive at the receiver. The receiver then detects and decodes the information encoded in these particles. Moreover, the signals in molecular communication are biocompatible, and require very little energy to generate and propagate. These properties make chemical signals ideal for many applications, such as biomedical application, environment application, where

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†This paper is an extended version of the paper which was accepted by BICT 2015[1]

the use of electromagnetic signals are not appropriate or not desirable.
Although MC has already existed in nature and has been used by micro-organisms, it was only recently that engineering a MC system has been proposed as means of communication at the micro-scale[7]. Macro-scale MC was not even considered until Dr. Nariman Farsad developed the first macro-scale test-bed for molecular communication[8], and later Dr. Nariman Farsad and the team from Yonsei University set up a multiple-input multiple-output molecular communication test-bed [9].
In [10], the first horizontal, modular and programmable platform for molecular communication in macro-scale was developed by Dr.Nariman Farsad, which makes a big leap in the development of molecular communication. Farsad et al. elaborate on the horizontal flow assisted propagation of molecular communication in a long range, but discusses little about the short range of molecular communication based on pure diffusion. In biological systems, the communications between nano-machines are in short range in most situations, also particles(information molecules) are precious resources, thus releasing large numbers of particles at once is impractical, we need to consider limitations on the amount of the transmission molecules. Also for the reason that in the vertical direction, the receiver can receive the peak value[11] of the information molecules. In nature there are many examples of information transportation in the vertical direction, such as *transpiration*[12] of plants, *biological pump*[13] in ocean, biological nitrogen removal at a vertically moving biofilm system[14], also it can be used to find the missing aeroplane under the water[15]. Therefore, we need to consider both pure diffusion and the vertical direction of information transmission.
In this paper, a vertical channel model was proposed, in which utilizes the isopropyl alcohol molecules to propagate in the vertical direction. Also inspired by Nariman Farsad's test-bed, a new platform was proposed to test the vertical channel model. The test-bed we set up only measures the peak value of the transmission, which is especially useful in biological system. For instance, when transmit drugs to a certain target, we need to consider the quantities of the drugs, neither too large nor too small. Moreover, we can utilize this mechanism to detect the sweat from the body, which will be used in body area nanonetwork[16].
This paper is organised as follows. In Section 2, we describe the basic model of molecular communication via diffusion. In Section 3, we describe the theory of vertical molecular communication model. In Section 4, we introduce the test-bed we set up and make a comparison with Dr. Nariman Farsad's. In Section 5, we analyzed the theory of molecular communication via diffusion, and show the difference of experiment result with the theoretical result. Finally, the non-linear least squares curve fitting method was used to get the coefficients of the test-bed in certain situation. In Section 6, we draw a conclusion on our works.

2. Molecular Communication via Diffusion

In this section, we review the basic model of molecular communication via diffusion(MCvD). The communication system is composed of a pair of nano devices, each called a nanonetworking-enabled node(NeN,ie.,nano node or nano robot)[17]. In MCvD, the NeNs communicate with each other through the propagation of certain molecules via diffusion[18, 19]. The MCvD system[20] is shown in Figure 1.

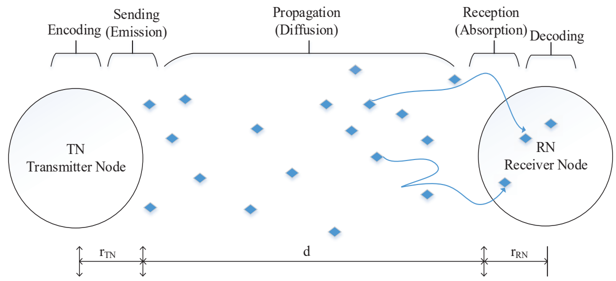

Figure 1. MCvD system

The general processes of MCvD system include Encoding, Sending(Emission), Propagation(Diffusion), Reception(Absorption), and Decoding[6, 21–23].
Encoding is the process in which a transmitter node translates information into information molecules that the receiver node can detect.
Sending is the process by which a transmitter node releases information molecules into the environment.
Propagation is the process during which information molecules move from a transmitter node to the receiver node through the environment.
Reception is the process by which the receiver node absorb the information molecules propagating in the environment.
Decoding is the process during which the receiver node reacts to the molecules.
In a MCvD system, communication pairs are assumed to be synchronized. Information is modulated on some of the physical properties of messenger molecules, it can be the number, type, or any other property of the messenger molecules. The movement of information molecules are modelled as either Brownian motion or diffusion process. The motion is governed by the combined forces caused by thermal energy of the medium. If we consider the diffusion processes of particles starting from its transmitter, then the concentration at distance d and time t is given as

$$f(d,t) = \frac{M}{(4\pi Dt)^{n/2}} \exp\left[\frac{-d^2}{4Dt}\right] \quad t > 0 \text{ and } d > 0. \quad (1)$$

where D is the diffusion coefficient[24], n is the dimension of the environment, and M stands for the amount of molecules. In this paper, we mainly consider one dimension environment. D depends on the temperature of the environment, viscosity of the fluid, and Stokes' radius of the molecules[25]. Equation (1) is also treated as the single impulse response for a point source(transmitter)[17].

3. Vertical Model of MC

3.1. Schema of the Vertical Model

As we know, different propagation scheme and modulation technique lead to different channel model. Generally, the molecular communication often happens in the free space, however, Guo et al investigated three kinds of bounded space propagation environment, such as the knife edge, the pipe, and the mesh channel[26]. And find that the propagation environment and shape of the channel are very important to boost the efficiency of molecular communication.

In nature, information can also be transmitted in the vertical direction. Such as, transpiration of plants, biological pump in ocean. Therefore, we propose a vertical channel model, which resembles Figure 2. As you can see, the transmitter and the receiver are in the same line in the vertical direction.

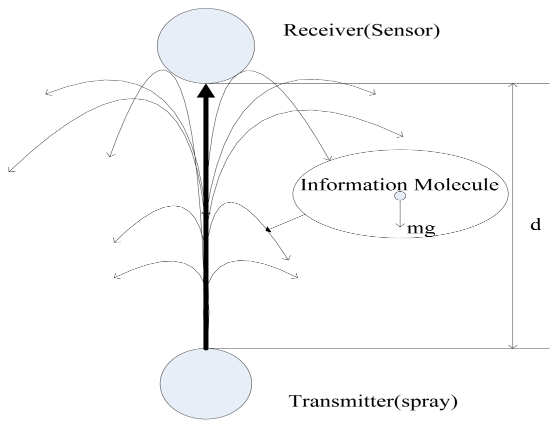

Figure 2. The vertical model of MC

In the vertical direction, the information is emitted from the transmitter, which looks like a spring. If properly positioned, the receiver can receive some molecules whose propagation range reaches the peak value[11]. In biological, the information molecules spread for every direction, and vertical diffusion is one of the common phenomenon. For instance, nutrition is transmitted in bloods of human or animals and pheromones are transmitted in plants, both of them can be in this direction sometimes. Therefore, it's necessary to investigate vertical model of molecular communication.

3.2. Impulse Response of Vertical Channel

In the MAC layer of the communication system, we separate the transmission into the same time slot. At the beginning of each slot, the transmitter emits information molecules. Considering the amount of the molecules at different time slot when the information molecules are transmitted in the vertical direction, the channel is basically affected by the transmitter and receiver's delay, the flow of the medium[27]. For single molecule, we need to omit the gravity, but for masses of molecules, the gravity should be taken into account. we denote the gravity of the mass molecules as mg in Figure 2.

In the uniform acceleration motion, if we know the initial velocity, the instant time , then we get the velocity of the object at time t. The movement of the object is described as Equation (2).

$$v(t) = v_0 + at \quad t \geq 0 \ . \tag{2}$$

where $v(t)$ is the velocity of the object at time t, v_0 is the initial velocity, a is the acceleration. If the velocity has the same direction with the motion of the object, then the a is positive and also the velocity will become faster and vice versa.

In each time slot, the sending of the information molecules at the sending process can be treated as the single impulse response[28].

Therefore, inspired by the uniform acceleration motion, we make the following assumptions:

1)The decrease of the concentration of molecules is proportion to the variation of time;

2)The initial velocity is regarded as the impulse response of the very start of emitting molecules.

3)The variation of gravity is a constant. Due to the flow may affect the gravity, we denote the final result of gravity as e, the concentration of the molecules which denotes $f(t)$. $f(t)$ can be regarded as the total variation of the concentration at different time t, then we get Equation (3).

$$f(t) = C_0 - et \quad t > 0 \ . \tag{3}$$

where C_0 is the initial impulse response, which is regarded as the total concentration of the molecules at the process of sending. Due to the direction of gravity and motion of the molecules are in the different direction, the concentration will decreases with time.

Regard the first part C_0, we should introduce several parameters to adjust the Equation (1). Due to the transmitter, receiver and the channel are in the same line, we only consider in one dimension environment($n = 1$), then we will get the Equation (4)

$$f(t) = \frac{a}{\sqrt{t}} \exp\left[\frac{-bd^2}{t}\right] - et \quad t > 0 \ . \tag{4}$$

where d is the distance between transmitter and receiver, and t is the time, parameter a corresponds to this part

$\frac{M}{\sqrt{4\pi D}}$ of Equation (1), which is related to the diffusion coefficient and the delay of transmitter and receiver, and b corresponds to the part $\frac{1}{4D}$ of Equation (1), which is affected by the diffusion coefficient, for the parameter e is related to the diffusion coefficient and the gravity of molecules. For the value of the coefficients, we will discuss in Section 5.2.

4. Test-bed for Vertical Model of MC

Inspired by Dr.Nariman Farsad's work[10, 29], we set up another kind of test-bed for macro-scale molecular communication in the vertical direction. In this section, we will elaborate on our test-bed which named "Ares".

4.1. Basic parts of Ares

The complete test-bed we set up is depicted as Figure 3.

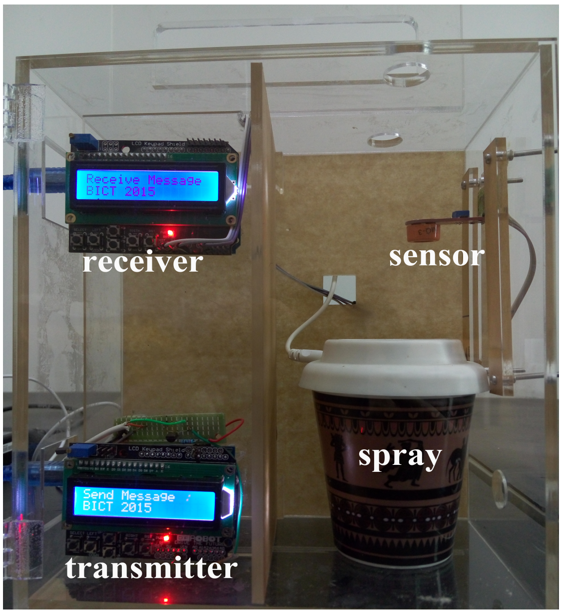

Figure 3. A test-bed for vertical molecular communication

As can be seen, the main parts of Ares is wrapped by the acrylic glass. In order to make the construction of Ares clearly shown, we draw a craft of the test-bed, which is shown in Figure 4. Ares is mainly consists of the transmitter, the receiver, the spray, and the alcohol sensor.

The transmitter is made of three parts, the LCD 1602 keypad shield, the microcontroller and the spray. The LCD 1602 keypad shield can be used to input some characters. The microcontroller is made of "Arduino uno R3" board, which is utilized to convert the information from the LCD keypad shield into binary stream, and then control the spray emitting molecules or not. The spray can emitting alcohol molecules.

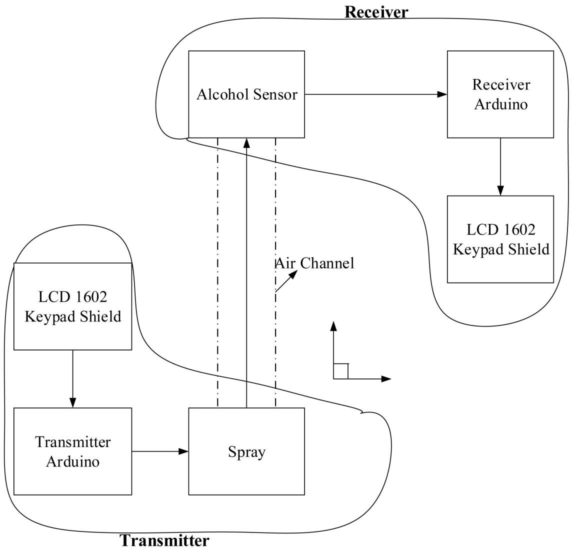

Figure 4. The craft figure of the test-bed

The receiver is consist of MQ-3 alcohol sensor, the microcontroller and the LCD 1602 keypad shield. At first, the MQ-3 alcohol sensor can produce a value from 0 to 1023 according to the concentration or the number of the alcohol molecules, then transmits the value to the receiver. Finally, the microcontroller at the receiver can demodulate the information from the alcohol sensor into "0" or "1", and show the decoded information to the LCD 1602 screen.

4.2. Communication Processes of Ares

Utilizing the keys of LCD keypad shield, we input the message "BICT 2015" on the LCD. Through a short program we made, each character of the message "BICT 2015" can be converted into ASCII sequence. By using the simple frame structure we defined, we add the header "11" and the tail "00000" to each ASCII sequence. Then the microcontroler of the transmitter detect the bit stream of the frame at the *encoding* process. For this test-bed, the modulation technique is concentration shift keying[30–32]. In other words, the information can be modulated into bit "0" or "1". When the microcontroller detects the bit is "1", it will control the spray emitting some alcohol molecules in the *sending* process. As to our test-bed, when transmitting bit "1", the spray will emit alcohol molecules for 100ms,and wait for 400ms. On the contrary, when sending bit "0", the spray will emit nothing, and wait for 500ms.

After emitted by the spray, alcohol molecules will propagate in the air channel from the spray to the alcohol sensor in the vertical direction. According to the concentration of the molecules arrived at the alcohol sensor, which will produce an analogy value to the microcontroller at the receiver side.

According to the variation of two consecutive values, the microcontroller will decide the transmitted information bit is "0" or "1". Later, the microcontroller will demodulate the bit stream into message and show it on the LCD screen.

4.3. Information Frame

In our test-bed we use seven bit ASCII to encode the information, then each text message is made of seven bit sequence. Figure 5 is a simple information frame we defined.
The infromation frame is made of three parts, the header, the packet, and the tail. The header is utilize to detect the information reach to the receiver, which consists of two bit "1". The packet is made of seven bit ASCII. The tail can make sure the sensor recover to the initial status, which is made of five bit "0". For example if we want to send letter "B", and the ASCII of "B" is "1000010", then the output of the bit sequence is "11100001000000". And the total number of the bit is 14. Through several times of experiments, in order to make the communication more reliable, sending each bit needs $0.5ms$. Then the total time for each character is $7s$. Therefore the transmission rate is 2bps.

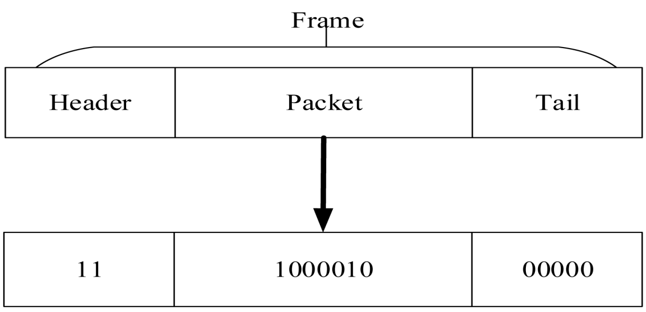

Figure 5. Information Frame

4.4. Comparison of "Kinboshi" and "Ares"

Here we make a brief comparison of Dr. Nariman Farsad's test-bed "Kinboshi" with our "Ares". As the Table 1 describes.

Table 1. The Comparison of Kinboshi[33] and Ares

Parameters	Kinboshi	Ares
mainly parts	fan, spray, Arduino controller	spray, Arduino controller
distance(m)	≥2	0.05-0.1
encode method	ITA2	ASCII
total information length	12	14
time for each character(s)	36	7
transmission rate(bps)	0.3	2

Through the comparison we can know that the distance between transmitter and the receiver of our test-bed is short than Nariman's. As we know, the main parts of nano-scale molecular communication are the nano-scale transceivers and the nano-scale distance between transmitter and receiver. In the nano-scale communication field, the shorter the distance the better. From this aspect, our test-bed(Ares) is better than Kinboshi. Though the distance of transceivers in our test-bed is still in macro-scale size, as the top-down method to make nano-scale devices, it is a necessary step.
Ares utilize the ASCII code instead of ITA2, because ASCII has seven or eight bit , which can encode 128 or 256 characters, including letters or numbers. However, the ITA2 can only express 32 characters, it is only fit to a few letters. For ASCII method, it is suit for wider range of characters.
For our test-bed, the total length of each character is $14bit$, which is longer than Kinboshi. Due to the transmission of each bit needs 0.5s, therefore, for our "Ares", transmitting each character needs 7 second, which needs less time than Kinboshi's.

5. Theoretical Model and Fitting Model

In this section, we present the difference of the theoretical models and the experimental data from our platform, also according to the experiment data and non-linear least squares method, we fitted a more accurate model for our test-bed.

5.1. Theoretical Models Versus Experimental Results

Through analyzing the system response, we compare the previously published theoretical models in Equation (1) with the experimental results. Table 2 summarizes all the experiment parameters we used in Ares.

Table 2. The Experiment Parameters

Parameters	Values
Distance between a transmitter and a receiver	10cm
Spraying during for each bit	100ms
Diffusion coefficient of isopropyl alcohol	$0.0993cm^2/s$[34]
Temperature(room temperature)	25°C=298K

If these parameters are used in the theoretical Equation (1), the system response can be calculated. Because the number of particles released by the transmitter is not known, we assume $M = 1$ and then normalize the plots by dividing them by their respective maximum values. Similarly the system responses obtained from experiment result is normalized with its maximum. By normalizing the plots, we compare only the shape of the theoretical results with the shape of the experimental results. For our experimental system response, we average the response of 6 different experimental trials to produce a single plot. Figure 7 shows the theory simulation versus the experiment simulation at different time.

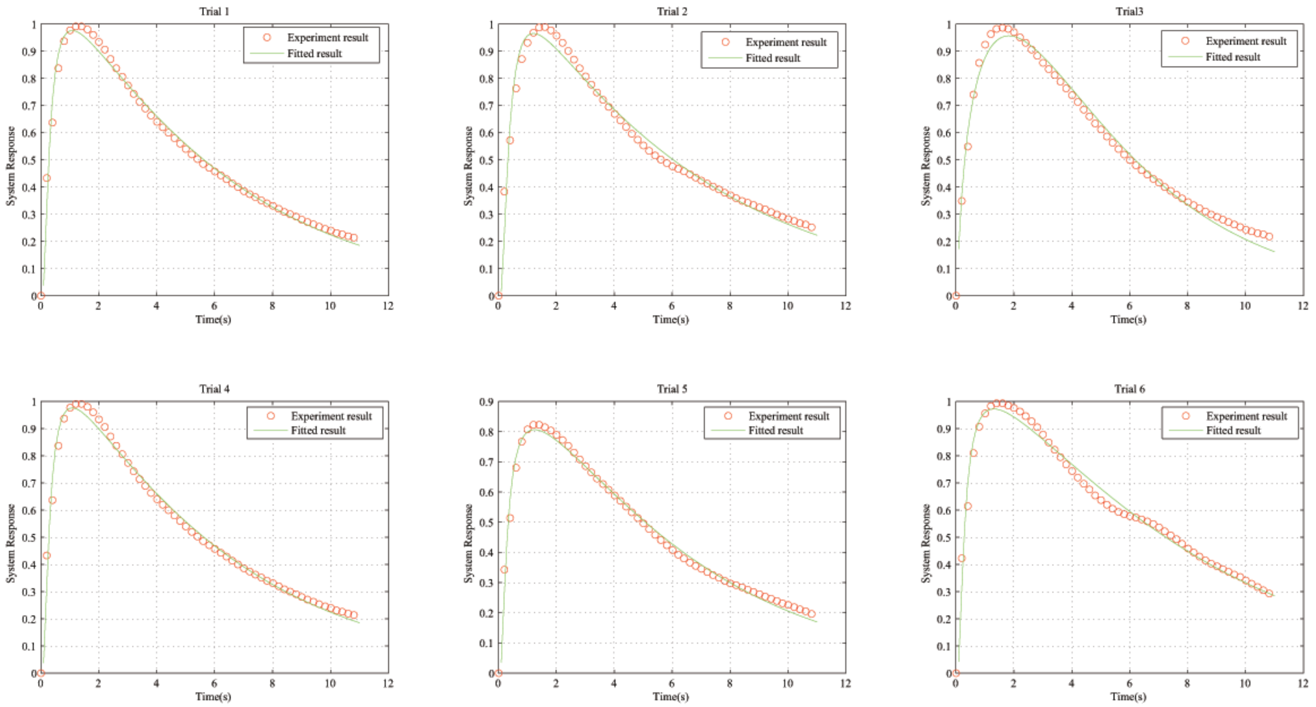

Figure 6. System response and the fitted model for set of 6 trials

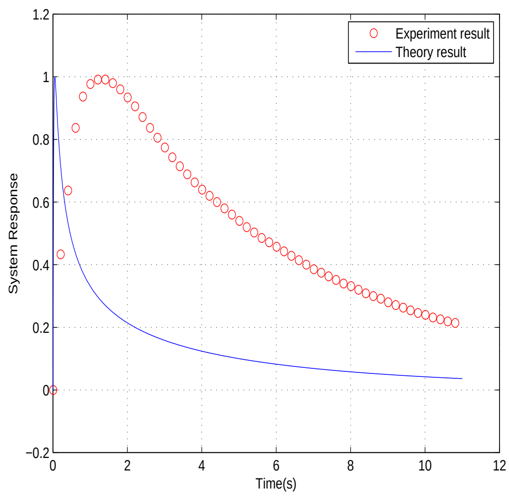

Figure 7. Comparison of the experimental data and theoretical models

According to the shape of the two curves, we find that the theoretical model reaches its peak early than the experiment model. Then we need to consider the delay in the experiment model[27]. The sensitivity of transmitter and receiver and the flow of the medium may lead to the delay. we may reduce the delay when we adjust the formula of the theoretical by adding or adjust some parameters, we may get a curve as the experimental curve. For the details we will discuss in the Section 5.2.

5.2. Fitting model

For the reason that only the first few seconds of the system response is typically used in practice for information transmission[8] in the molecular communication. Also, in order to get a better and more accurate result, we use the system response value of the first 11 seconds to fit the curve of the proposed model.
Through the experiment data we got from our test-bed, we use non-linear least square curve fitting method[35] to estimate the coefficients of a, b, e. In Figure 6 shows the 6 trials of the experiments and the fitting models from the data we get. And the circle is the data from the test-bed, and the line is the fitting models.
After six trials of experiments, we choose coefficients of a, b, e as the average of each trials. Then we get coefficients of a, b, e are 1.8788,60.4567,0.0301 respectively, and d equals $0.1m$. Finally, we get the following equation from Equation (4).

$$f(t) = \frac{1.8788}{\sqrt{t}} \exp\left[\frac{-0.6045}{t}\right] - 0.0301t \quad t > 0 \ . \qquad (5)$$

Again we do the experiment with the coefficients we get, and plot the results as the Figure 8.

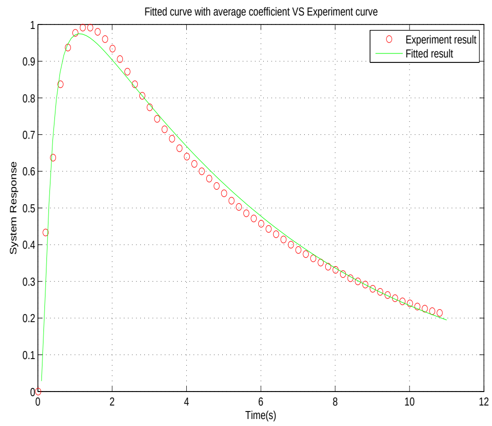

Figure 8. The fitting circle vs the experiment line

6. Conclusions

In this paper, we showed a vertical MC channel model based on the alcohol molecules, and considered the gravity. From Figure 7, we know that the experiment results have some difference from the theoretical results, but through comparing the Equation (4) with the experiments results, we can get the coefficient of the Equation(5) through experiments with non-linear least squares method. The model can be used in some biological field, such as transpiration of plants, biological pump, to help improve the efficiency of information transmission. Also, in body area nanonetwork, we can utilize this mechanism to detect the sweat from the body. We model the channel only in the certain environment, there are still many details we need to investigate. We only studied the simple information frame, and in the future, we can make the frame more detail to boost the communication efficiency. Also we will investigate the Inter-Symbol-Interference between two consecutive symbol slots by using different modulation techniques. In order to make the test-bed more accurate, and more reality to the real molecular communication, we may try to eliminate some assumptions and the normalization requirement. Also, we may estimate the distance between transmitter and receiver to adaptively change the symbol duration, which has a significantly meaning in the nano-scale communication.

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