Hibrit MEMS-tabanlı Moleküler Haberleşme Sistemi Hybrid MEMS-based Molecular Communication System

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***Özetçe* —Bu bildiride, mikro elektro mekanik sistem (MEMS) tabanlı bir ortama entegre edilmiş bir moleküler iletişim bağlantısını ele alıyoruz. İletişim güvenilirliğini artırmak için moleküler iletişim sistemine akustik cımbızlama teknikleri uyguluyoruz. Bu hibrit sistemi simüle etmek için sonlu eleman metotları kullanıyoruz. Performans ölçütü olarak sembol hata oranını türeterek önerilen sistemin sıvı akışının varlığında güvenilir iletişimi kolaylaştırdığını ve performansının sıcaklık gibi dış etkenlere karşı dayanıklı olduğunu gösteriyoruz.**
Anahtar Kelimeler—Moleküler haberleşme, MEMS, akustik cımbızlama, mikroakışkanlar.

***Abstract*—In this paper, we consider a molecular communication link integrated in a micro-electro mechanical system (MEMS) based environment. We apply acoustic tweezing techniques to the molecular communication system to increase communication reliability. We use finite element methods to simulate this hybrid system. By deriving the symbol error rate as the performance metric, we show that the proposed system facilitates reliable communication in the presence of fluid flow and its performance is robust against external factors, such as temperature.**
Keywords—Molecular communication, MEMS, acoustic tweezing, microfluidics

I. Introduction

Molecular communication (MC) is a process that exists in nature where the information is conveyed by releasing (messenger) molecules into the medium. These molecules propagate through the channel via diffusion by Brownian motion. In engineered molecular communication, a group of nanomachines are designed to communicate so that a smart collaboration can be achieved at the transmitting and receiving sides.

In MC, a diffusion based propagation is one of the most commonly used channel model [1], where the randomness of the channel lead to higher symbol error rate. Flow assisted propagation [1] has been proposed to increase the transmission rate but it is very sensitive to minor environmental changes.

Another mode of propagation that has been investigated over the years is to assist the motion by the use of special carrier substances, such as protein motors [2], bacteria [3], or magnetic nano particles (MNPs) [4]. In all of these works, messenger molecules are guided towards the receiver, but the transmission is still slow and counts on the diffusion process through the channel. To increase the reliability of the channel [4] relied on maintaining a magnetic field gradient.

In this work, we investigate the use of micro-electromechanical systems (MEMS) in molecular communication. MEMS has faciliated the study of cell handling and manipulation by translating it on a lab on a chip (LOC) environment by combining microfluidics and acoustic standing wave technology. Inspired by the benefits of acoustic tweezing in various disciplines, we investigate their benefits in molecular communication and make the following contributions:

We propose the use of 2D ultrasound transducers to guide the messenger molecules towards the receiver. This technique would give a complete hold over the transmission channel, which will be less susceptible to noise resulting through fluid flow.

To illustrate the utility of acoustic tweezing, we consider a two dimensional bounded environment which can be considered as a simple abstraction of a microfluidic channel. We use finite element modeling to get exact solutions and for the designed and simulated model, we calculate the symbol error rate (SER) to evaluate the system performance. We show that by employing a systematic channe, the accuracy of the molecular communication increases along with the transmission rate.

II. System Model

The effectiveness of the proposed technique is tested by designing and simulating a linear planar acoustic resonator in ANSYS 16.1, a commercially available finite element analysis tool.

Acoustic tweezers are devices that use ultrasound for particle handling and have gained much attention over the past due to their simple and cost-effective design [5]. The simulated one dimensional standing wave devices utilize axial radiation forces of one dimensional capacitive micromachined ultrasonic transducer (CMUTs) array and a reflector surface to trap and manipulate particles in the nodes or antinodes.

The information carriers are enclosed in a channel of height h with $0 \leq y \leq h$, and infinite width in the $x - -y$ plane such that $-\infty \leq x \leq \infty$, as shown in Figure 1. A total of N_e transducer elements are simulated with 50 μm side length, 2 μm thickness, and 2.5 MHz operating frequency. As the devices are operating in air, free field boundary conditions are applied on the top and bottom of the devices, whereas second-order absorbing boundary conditions are applied at the lateral edges of the fluid layer to absorb the acoustic energy incident at the boundary.

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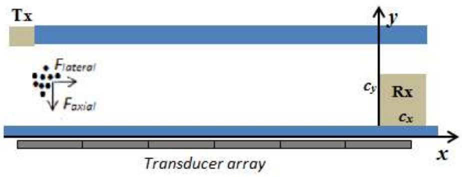


Figure 1: System model illustration

A. Channel Model

We consider a typical MC system, with a transmitter and a receiver placed d distance apart in a channel. In the scenario under consideration, the transmitter is placed at $x = d$ and $y = h/2$. The information symbols that are to be transmitted, $b[k]$, are modulated with on-off keying (OOK) [6]. The transmitter, therefore, releases N_{TX} molecules for $b[k] = 1$ and no molecules are released for $b[k] = 0$. The propagation of molecules depends on the switching of the transducer elements, see Figure 1.
The receiver RX is an absorbing body with width c_x and height h. The receiver absorbs the incoming particles by taking samples at times $kT_s + \tau_r$, where T_s is the switching time of an element, τ_r is the time the particles reorient under the created pressure gradient, and k is the number of elements, satisfying $2 \leq k \leq N_e$. The symbols are detected by counting the number of received carriers and a threshold metric ξ is defined, satisfying

$$\hat{b}[k] = \begin{cases} 0, N_{rx} < \xi \\ 1, N_{rx} \geq \xi \end{cases} \tag{1}$$

B. Acoustic Tweezing

We model $10\mu m$-wide non-active particles as carriers that experience a continuous drag force F_{drag} from the surrounding fluid. The transducers generate standing waves that are responsible for creating potential and kinetic energy gradients that exert forces (called acoustic radiation force) on the carriers [7]. The main component of the force is the axial primary radiation force, which is given as:

$$F_{axial} = 4\pi E K \varphi \sin(2Kx).R^3, \tag{2}$$

Here K is wave number, R is the particle radius, x is the particle position in the direction of wave propagation, and φ is the acoustic contrast factor, respectively. The acoustic contrast factor is given as

$$\varphi = \frac{\rho_p + (2/3)(\rho_p - \rho_f)}{2\rho_p + \rho_f} - \frac{\rho_f c_f^2}{3\rho_p c_p^2}. \tag{3}$$

E is the acoustic energy density, given by

$$E = \frac{P^2}{4\rho_f c_f^2}, \tag{4}$$

where P is the maximum pressure, ρ_f and ρ_p are the densities of fluid and the particle, respectively. c_f and c_p are the speed of sounds of fluid and of the particle.
The lateral component of the radiation force will trap particles above the center of active elements. An estimate of lateral trapping force is obtained from the viscous drag force F_d, which is given by Stoke's law and is a multiple of the friction coefficient ζ and velocity of the particle v. ζ is given by $6\pi\eta R$, where η is the the viscosity of water.

III. Performance Analysis

In this section, a performance assessment based on the number of received symbols in error is made. In order to do that the distribution of the confined particles and how they react when the elements are switched on need to be understood.

A. Distribution of confined carriers

The acoustic tweezing depends on the switching of the transducer array. If all elements are activated at the same time, a pressure well is generated, see Figure **??**. All particles are accumulated at this well, due to the acoustic radiation forces (2). By switching the transducer elements, the potential well can be created at any desired location and it can be manipulated accordingly. For the time $0 \leq t \leq T_{s1}$, the first element of the transducer array is made active, which creates a pressure gradient centered above the active elements. The carriers, are therefore, confined in the harmonic trap and a Boltzmann distribution is reached [8].

$$p(x,t) = \frac{k}{\pi\zeta D} e^{(-\frac{kx^2}{\zeta D})}, \tag{5}$$

where k is the spring constant and D is the translational diffusion coefficient and is defined in terms of Boltzman constant k_b and the temperature T as

$$D = \frac{k_B T}{6\pi\eta R}. \tag{6}$$

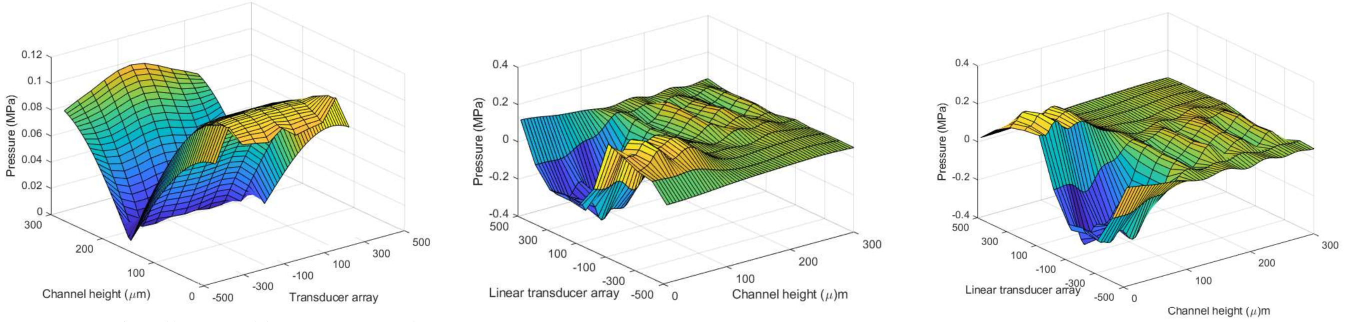
The maximum density of the particles occurs at the trap center $r = 0$, see Figure 3. At the next time instant, when the first trap is switched off and the next element of the linear array is made active, such that, $T_{s_1} \leq t \leq T_{s_2}$, the particles are pulled towards the new trap location. The acoustic traps can draw particles within $\sim 100\mu m$ radius from the trap center [9]. The particles are now centered above the next element of the array. This process can, therefore, be repeated down the array elements by sequentially switching N_e transducer elements, resulting in the propagation of carriers towards the receiver's end.

B. Probability of Particle Observation

The probability of observing a particle at the receiver's end can be found by integrating equation (2) from -$c_x/2$ to $c_x/2$ as

$$P_{ob,x}(t) = \frac{1}{2}\left[\text{erf}\left(\frac{\bar{x}(t)+\frac{1}{2}c_x\sqrt{\frac{1}{\alpha t}}}{\sqrt{\pi t/\alpha}}\right) - \text{erf}\left(\frac{\bar{x}(t)-\frac{1}{2}c_x\sqrt{\frac{1}{\alpha t}}}{\sqrt{\pi t/\alpha}}\right)\right], \tag{7}$$

where erf (.) is the error function, $\alpha = k/\zeta D$ and $\bar{x} = d - vt$, considering that the particles arrive at the RX at time $t = d/v$. By the principle of half wave resonators, the particles are agglomerated in the center of the channel and therefore the probability of observing a particle in the z-coordinates will be $P_{ob,z}(t) = 1$. The probability of observing a particle within the receiver's volume is then obtained as $P_{ob}(t) =$



(a) Potential well created by activating the transducer array

(b) Potential node created by turning on first from the two elements

(c) Potential node created by turning on the second from the two elements

Figure 2: Generated pressure gradient by turning on the second element of the array

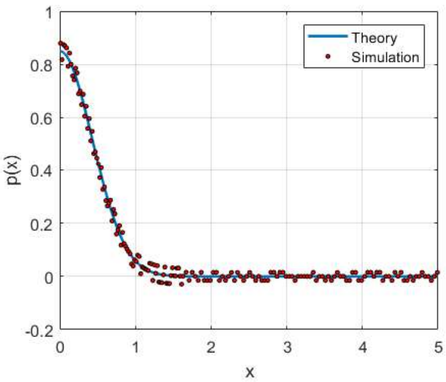


Figure 3: Distribution of particles in the microfluidic channel

$P_{ob,x}(t) \times P_{ob,z}(t) = P_{ob,x}(t)$. The expected number of molecules arriving at the receiver can be obtained as:

$$N_{ob}(t) = \sum_{i=1}^{N_{TX}} P_{ob,i}(t), \tag{8}$$

where $P_{ob,i}(t)$ is the probability of observing the i^{th} particle at a time t. $P_{ob,i}(t)$ is a function of the particle's size but as the particles propagate in the form of an agglomerated crystal, we can say that the contribution of an individual particle's size can be ignored and therefore each particle will have the probability P_{ob} at the receiver.

C. Symbol Error Rate

In the detection process, the receiver counts the incoming carriers at a time equal to the switching time of the transducers (T_s) plus τ_r, denoted as τ_r'. Therefore, the expected number of observed molecules $\bar{N_{rx}}$ at the receiver within this time slot is given as [10]

$$\bar{N}_{rx}(j) = \sum_{i=0}^{j} b[i] N_{ob}((j-i)Ts + \tau_r'). \tag{9}$$

An error occurs when the j^{th} received bit, $\hat{b}[j]$, is not equal to the sent bit, i.e., $\hat{b}[j] \neq b[j]$, which will happen when the number of observed molecules is less than ξ, as given by the decision rule in (1). Thus, the probability of observing this error is denoted as p_ξ and it is equal to $Pr(N_{rx} \leq \xi; b[0 \leq x \leq j)$. By using the same reasoning as [10], N_{rx} can be approximated as a Poisson random variable centered around $\bar{N_{rx}}$ in which case $p_\xi = Pr(N_{rx} \leq \xi - 1; b[0 \leq x \leq j)$ is the Poisson cumulative distribution function with mean $\bar{N_{rx}}$ and evaluated at $\xi - 1$.

By means of acoustofluidics, the molecules are attracted towards the center of the active element, which is activated at the time instant T_s and reorient themselves in τ_r. The particles, in the form of an agglomerated crystal, stay in the trapping site until the trap is switched off. However, at the time $2T_s$, the second element of the transducer array is switched on and the molecules propagate towards the next trapping site. Therefore, the molecules are made to be spatially separable and this eliminates the chances of inter symbol interference (ISI).

As there is no ISI, then for $\xi \geq 1, b[j] = 0$, is always detected correctly, as no molecules are sent for $b[j] = 0$. If $n_{rx} = 1$, then $\bar{N}_{rx}(j) = N_{ob}(\tau_r')$. Therefore, for equiprobable symbols, the probability of error is minimized when the decision metric is kept as 1 and the symbol error rate for a Poisson random variable simplifies to

$$P_{ser} = \frac{1}{2} e^{\bar{N}_{rx}(\tau_r')}. \tag{10}$$

IV. Performance Analysis

The first element of the transducers is biased with 60V DC and is driven with 12V AC signal. The generated acoustic wave creates a pressure gradient and exerts forces on the induced carriers. On average, a particle experiences $130pN$ axial force and $2.5pN$ lateral force. The parameters used for the simulation are given in Table 1. The receiver takes the

Parameter	Value	Parameter	Value
Array thickness	$2\mu m$	d	0.6mm
c_f	1500 m/s	η	1×10^{-3} kg/ms
c_p	1958 m/s	h	300 μm
ρ_f	1000 kg/m^3	ξ	1
ρ_p	1055 kg/m^3	c_x	0.1 mm
Particle radius	10 μm	c_z	0.17 mm

Table I: Parameters used in FEA simulations sample at $\tau_r' = 2s$. The symbol error rate is evaluated using (10) with $\xi = 1$ for different number of transmitter particles. We note that the radii of the transmitted particles do not have a significant effect on the symbol error rate. In Figure 4, we compare the evaluated SER with the symbol error rate when there is no trapping force and the particles are free to move by the typical diffusion process. The achievable throughput of

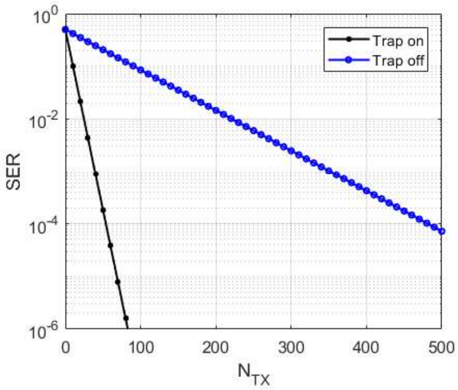


Figure 4: Symbol error rate evaluated at two different scenarios, when the trap is on and when the particles are allowed to diffuse through the channel

the system is calculated by evaluating the number of molecules arriving at the receiver at $(d/v)^{th}$ time instant. The data rate of this technique is design-specific and so it relies on the specifications of the transducer array. In Figure 5, we present the throughput of the system for different number of released molecules, where the symbol duration was kept as $2s$.

V. Conclusion

In this paper, we explored a hybrid MEMS based molecular communication system. We showed that molecular communication could benefit from an ultrasonic acoustic tweezing technique, where the carriers are made to propagate through the channel via ultrasound waves. We used finite element methods to simulate the transmission environment and evaluated symbol error rate to show that a guided propagation medium not only increases the transmission rate but also increases the accuracy as compared to a pure diffusive channel.

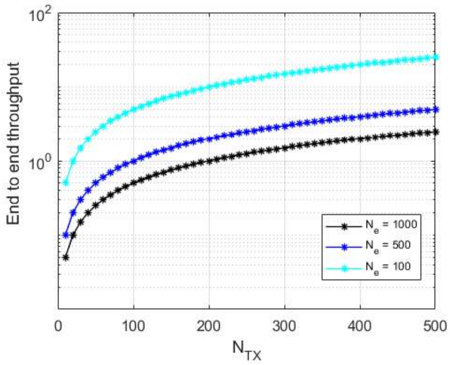


Figure 5: Throughput of the system evaluated at different number of array elements (N_e) when (N_{TX}) number of molecules are released

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