

Characterization of Dielectrophoresis Based Relay-Assisted Molecular Communication Using Analogue Transmission Line

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ABSTRACT Increase in research focus on developing lab-on-chip based devices like Body-on-chip and Organ-on-chip, have led to a higher number of functional entities in lab-on-chip. This, in turn, has led to increasingly complex microfluidic channel networks. Thus, there arises a need to characterize the microfluidic networks and establish communication among various entities of lab-on-chip. Electric circuit analogy is one of the options for the characterization of such a microfluidic network. Further, the dielectrophoresis relay-assisted molecular communication system can help in establishing interconnection among various entities using molecular communication. We propose to use an electrical transmission line technique to model and characterize the dielectrophoresis relay-assisted molecular communication system. We use transmission line parameters- resistance, inductance, and capacitance for characterizing the said molecular communication system. The numerical results obtained show that the peak concentration reduces as a function of distance, and the attenuation of the transmitted signal decreases with the increase in the number of relays in the system. This implies that the dielectrophoresis relay-assisted molecular communication system can help in transmitting low-frequency concentration signal with low attenuation. The results obtained are consistent with those obtained with already existing techniques. Thus, the transmission line technique can be utilized for characterizing a microfluidic system for molecular communication.

INDEX TERMS Attenuation, dielectrophoresis, lab-on-chip, molecular communication, relays, transmission line.

I. INTRODUCTION

Body-on-chip is a biomimetic microsystem engineered to emulate the structural and functional complexity of the human body. Such a system helps in the analysis of complex interconnected biochemical and physiological responses across multiple organs micro-engineered on a chip known as organ-on-chip (OOC) [1]. Microfluidic OOCs offers the possibility of multi-scale architecture and tissue to tissue interfaces. Moreover, the presence of microfluidic channels (MFCs) in OOC allows the cells to be exposed to various mechanical forces, which help in organ development, such as tension, compression, and fluid shear stress [2]. These biomimetic microsystems are essentially lab-on-chip (LOC) devices, interconnected through a network of MFCs. The interconnection of LOCs through the MFC network

provides a medium to communicate and share information among all connected entities in a biocompatible environment [3].

Molecular communication (MC) is a bioinspired communication wherein molecules are used to carry messages between transmitters (T_i) and receivers (R_j) [6]. MC is a technique envisioned to enable communication in environments where other communication methods are not applicable. It provides a very low communication rate and is preferred when biocompatibility is imperative. Thus, incorporating MC principles on MFCs can assist in communication and information sharing between different LOCs of biomimetic systems and all functional entities within LOC [4], [5]. Among various techniques for transportation of information-carrying molecules on LOCs [7]–[9] dielectrophoresis (DEP) is one of the essential techniques to transport molecules in LOCs effectively. DEP is a phenomenon in which neutral molecules move under the influence of a nonhomogeneous

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electric field [10]. DEP relay-assisted MC systems can help to overcome several limitations of MC, such as low bandwidth, range of communication, and synchronization between T_l and R_l [11].

In LOC, it is necessary to transport information from one working entity to another through MFCs. The rapid increase of functional blocks in LOC has led to an increase in the interconnect area of MFC's, which results in more complex MFC networks. This adds to the challenge of precise control of concentration and flows in MFC networks. The mapping of electric circuit elements onto the corresponding MFC elements facilitate in designing complex MFC networks with 1D like microchannels [12]. Despite limitations, electric circuit analogy has been used in designing several applications involving concentration and flow in MFC networks. In [13], a droplet-based hydraulic controlled microfluidic network was implemented for interconnecting and embedding telecommunication principals onto the LOC using electric circuit analogy. In addition to the above application, synchronization and regulation of droplet traffic were brought in practical use by using electric circuit analogy [14], [15]. An electric circuit analogy has also been widely used in analyzing electrokinetic flow in MFCs [16]. A universal microfluidic concentration gradient generator used for serial dilution to reduce the concentration sample in microfluidic flow was designed using electric circuit analogy [17]. Furthermore, an electric circuit analogy can be used for analyzing frequency-dependent flow by accounting for resistive, capacitive, and inductive properties of MFC [18].

Hagen-Poiseuille's law is analogous to Ohm's law with analogy of electrical components to its corresponding mechanical equivalent wherein the pressure drop is analogous to the voltage drop, the volumetric flow rate to the current, the hydraulic resistance to the electric resistance, hydraulic compliance to the electric capacitance and inertia of fluids to the electrical inductance [19]. The flow rate is proportional to pressure drop, and the proportionality constant is the hydraulic resistance. Moreover, electrical resistance leads to the dissipation of energy in the form of Joule heating, while hydraulic resistance leads to the viscous dissipation of mechanical energy into heat by internal friction in the fluid. Furthermore, hydraulic compliance, also known as hydraulic capacitance, it is the change in volume of fluid due to change in pressure, hydraulic capacitance exists because of fluid compressibility and non-rigidity of channels [12], [19]. Table 1 summarizes the analogy between microfluidic/hydraulic circuits and electric circuits. A two-port electric network segment with series resistance (r_s), inductance (λ_s) and shunt capacitance (C_s) together is termed as transmission line is shown in Fig. 1. The transmission line is an integral part of communication systems, as it supports the propagation of transverse-electro-magnetic (TEM) waves and transmits a signal from one point to another point [20]. It has been used for modeling time-variant flows for various applications involving the solution of diffusion equation [21]–[23]. It has also been used in analytical modeling of an in-vivo system

TABLE 1. Electrical Circuit Analogy: Highlighting similarities between microfluidic and electrical parameters.

Symbols	Electrical Parameter	MFC Parameter
ϕ	Voltage (Volts)	Pressure (Pascal (Pa))
i	Current (Ampere)	Volumetric flow (m^3/s)
r_s	Electric resistance (Ω)	Hydraulic resistance ($Pa\ s^3/m$)
C_s	Electric capacitance (F)	Hydraulic compliance(capacitance) (m^3/Pa)
λ_s	Electric inductance (H)	Hydraulic inductance (Fluid inertia)

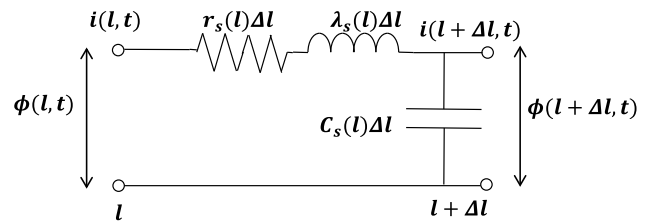


FIGURE 1. Distributed circuit for lossy transmission line segment of length Δl .

such as arterial flow and systemic circulation [24]. Since the transmission line is an important part of the communication system, therefore it can be useful in the analysis of important parameters of MC like attenuation of signals, the reflection of signals and bandwidth. In this paper, we model the DEP relay-assisted MC system using the transmission line technique. To the best of our knowledge, this is the first time a diffusion based MC system has been modeled using the transmission line technique. Here we characterize the MC parameters using transmission line parameters such as per unit length resistance, capacitance, inductance, and characteristic impedance of transmission line. We also analytically derived the concentration profile of molecules after time t considering a lossy transmission line and analyzed the variation in peak concentration value when subjected to frequency dependent attenuation. Furthermore, we derive the transfer function of the system dependent on the transmission line parameter. Further, the change in attenuation and the normalized magnitude of the transmitted concentration signal with the varying number of DEP relays are also investigated. Fig.2 illustrates a visual summary of the work done in this paper.

The remaining paper is organized as follows. In Section II, we present the system model. In Section III, Transmission line Modeling of MFC with DEP relays is discussed. Attenuation and spreading of a pulse propagating in MFC are derived in Section IV; subsection IV-A presents the derivation of the transfer function of the presented model. Numerical results are detailed in Section V. Finally, we present the concluding remarks in Section VI.

II. SYSTEM MODEL

If transmitted information is encoded in the concentration of specific molecules, this is referred to as concentration encoding. The information is considered to be successfully

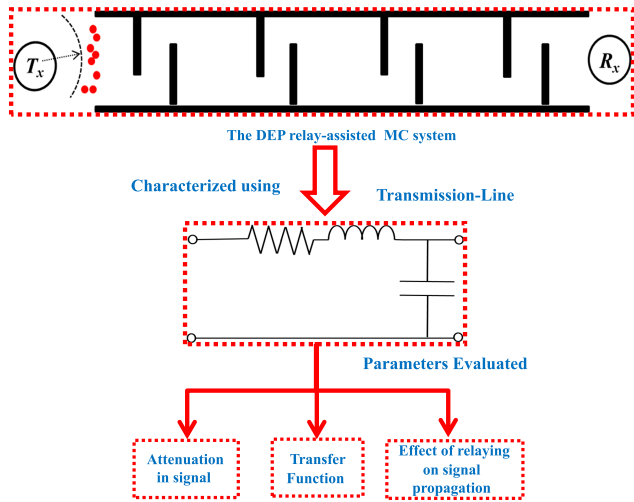


FIGURE 2. A graphical description showing that the DEP relay-assisted MC system is modeled using transmission line, and parameters such as attenuation in signal, transfer function, and the effect of relaying are evaluated.

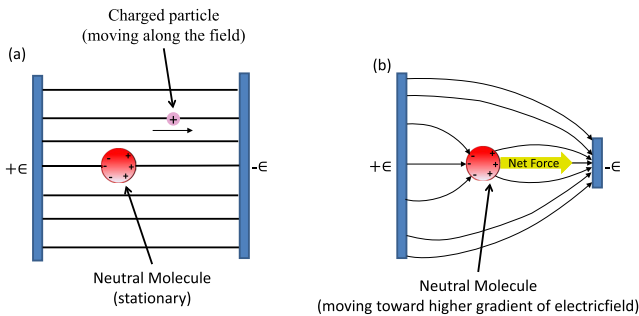


FIGURE 3. (a) Schematic of uniform electric field applied to neutral and charged molecule (b) Schematic of nonuniform electric field in neutral molecule.

delivered, if the concentration of transmitted molecules at R_l is above a certain threshold value. Thus, it is essential to maintain a signal strength at R_l for the detection of a signal, which can be challenging to maintain at the nanomachine level. The absence of prominent force in diffusion dependent MC results in attenuation and temporal spreading of a signal at R_l . A solution to the problem of attenuation and temporal spreading of a signal is necessary for establishing a reliable molecular communication in the diffusive channel, and this can be mitigated using the DEP relay-assisted MC system. DEP assisted transport process relies on applying and switching ON and OFF of asymmetric electric field between electrodes [11]. In this work, authors gather control over random diffusion of molecules by applying an asymmetric potential to periodically placed electrodes in the diffusive medium and thus exploit the DEP phenomenon of creating a rectified drift. The molecule experiences a force F_{DEP} when subjected to an asymmetric electric field ϵ shown in Fig. 3.

$$F_{DEP} = f(\omega, \epsilon, R, G) \cdot \nabla |\epsilon|^2. \quad (1)$$

The DEP force is a function of the frequency (ω) of an applied electric field (ϵ), the radius of the molecule (R), permittivity and conductivity (ϵ, G) of both the molecule and the medium,

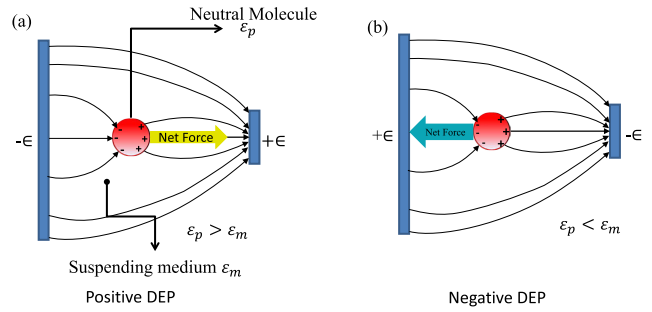


FIGURE 4. Direction of neutral molecule movement based on DEP response (a) positive DEP $\epsilon_p > \epsilon_m$ (b) negative DEP $\epsilon_m > \epsilon_p$.

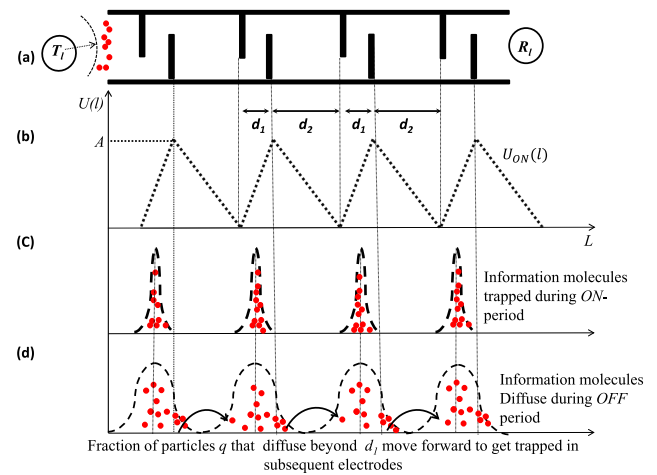


FIGURE 5. Schematics of DEP-relay-assisted MC system (Not to Scale) (a) Interdigitated electrode pairs with T_l and R_l , (b) Applied sawtooth (asymmetric) potential (U_l) of an amplitude A for t_{on} duration, (c) Molecule trapped during ON duration, when DEP is active, (d) When DEP force is removed, the molecule freely diffuses during OFF period.

and on the square of the electric field gradient. Since the force has frequency dependent behavior, if the applied frequency is greater than a certain critical frequency, molecules are attracted to maxima field intensity (positive DEP) else the molecules are attracted to the minima field intensity (negative DEP) shown in Fig. 4. By using either Positive DEP or negative DEP, molecules can be collected/captured by skilfully modulating the electric field in space [10]. Fig. 5 shows a schematic of the system and the process. The brief description is as follows. In Fig. 5(a) the system consists of a transmitter T_l which emits an impulse of N molecules (i.e., $N\delta(t)$) in to the channel at time $t = 0$ and R_l which receives the molecules. The channel consists of interdigitated electrode pairs periodically placed between T_l and R_l . Whereas d_1 is the distance between pair of interdigitated electrode and d_2 is distance between the two consecutive pairs of interdigitated electrodes, with $d_1 < d_2$. Such a placement of electrodes generates an asymmetric spatial configuration. Fig. 5(b) shows asymmetric sawtooth potential $U(l)$ of amplitude A applied periodically to interdigitated electrodes for t_{on} time and switched off for t_{off} time. Fig. 5(c) shows molecules trapped (due to DEP phenomena) in between the pair of interdigitated electrodes, in t_{on} duration, as depicted by a sharp peak of

concentration of molecules. Fig. 5(d) shows that molecules diffuse freely so that the concentration at the end of t_{off} time is a Gaussian distribution centered at the same points. Thus, the result of the ON-OFF cycle is that each electrode acts as a buffer and a relay in the system. The molecules that have diffused distance greater than d_1 will be retrapped in subsequent electrode upstream, as shown in Fig. 5(d) by means of an arrow. Thus, the advantage of the DEP relay-assisted MC system is that it produces a net unidirectional drift towards R_l . Therefore, this helps in maintaining the required molecule concentration strength for reliable MC. In [11], the probability of information rate is governed by design parameters such as total time $t_c = (t_{on} + t_{off})$ and the number of relays placed between T_l and R_l (which in turn, decides the maximum repeater-less distance of a molecule). Molecules considered here are spherical in shape with a neutral charge and homogeneous dielectric constant, placed in a lossy medium. System considered here is assumed to be one dimensional, with the following assumptions: (i) electrodes considered here are planar, as a result, electric-field is predominantly confined within the plane of electrode; (ii) DEP force decays with increase in height, as a result, movement of molecules is extremely near to the electrode surface; (iii) the area of R_l is significantly larger than the molecules received; (iv) the length of the channel is significantly more than the height, so that the shunted DEP driven movement (net drift of the molecule) along L , in time, traverse much greater distance than height; (v) electric field present along the width of the channel is time invariant. Moreover, electrical circuit analogy is best suited for one-dimensional microchannels [12]. Consequently, we consider 1D Fokker-Planck equation describing the movement of molecules in spatially periodic, but asymmetric potential which is expressed in [25] as:

$$\frac{\partial p(l, t)}{\partial t} = -\frac{\partial}{\partial l} \left(p(l, t) v_p - D \frac{\partial p(l, t)}{\partial l} \right). \quad (2)$$

Here $p(l, t)$ is the probability density of molecules in the space-time coordinate system, v_p is propagation velocity of the molecule due to potential $U(l)$ and D is the diffusion coefficient of the molecule. During t_{off} period when the potential is switched off the movement of molecules is dictated by Brownian motion; subsequently, the probability distribution of molecules at l and at time t_{off} is expressed as:

$$p(l, t_{off}) = \frac{\exp(-l^2/4Dt_{off})}{\sqrt{4\pi Dt_{off}}}. \quad (3)$$

The necessary condition to generate and maintain the net forward flux of molecules is $U(l) \gg K_B T$. Where K_B is Boltzmann constant, and T is the equilibrium temperature. The other important parameters which influence the net forward drift are spatial asymmetry parameters d_1 and d_2 . If conditions for net forward drift are satisfied, then it is possible to fix a value of t_{off} such that the probability of forwarding diffusion q is greater than the probability of molecule moving backward. The probability of molecules moving forward q

and the propagation velocity v_p is expressed in [25] as:

$$q = 0.5 \operatorname{erfc} \left(\frac{d_1}{\sqrt{4Dt_{off}}} \right), \quad (4)$$

$$v_p = ql/t_c. \quad (5)$$

Let $c(l, t)$ be the concentration of molecules at location l and time t , then $c(l, t) = Np(l, t)$, where $N (\gg 1)$ is total number of molecules thus, (2) can be rewritten as:

$$\frac{\partial c(l, t)}{\partial t} = -v_p \frac{\partial c(l, t)}{\partial l} + D \frac{\partial^2 c(l, t)}{\partial l^2}. \quad (6)$$

III. TRANSMISSION LINE MODELING

In this section, we model an inter relay segment of the DEP relay-assisted MC system using the transmission line technique. Here we obtain the differential equation for voltage on a lossy transmission line and show its equivalence to the Fokker Planck equation (6). Further, we characterize the MC parameters using transmission line parameters.

As mentioned previously in Section II, the DEP force also depends on the permittivities of molecules transmitted, and it's medium. The permittivity of the medium is complex in nature (i.e., frequency dependent), which makes the medium lossy, and the presence of two different complex permittivities [10] (i.e., medium and molecules) creates a non-homogeneous surrounding. Thus, because of lossy medium and non-homogeneous surroundings, we consider a non-uniform lossy transmission line segment of length Δl shown in Fig. 1. In this schematic of transmission line, we consider $\phi(l, t)$ is voltage (this may be noted that the voltage $\phi(l, t)$ is arbitrary voltage applied to the transmission line segment, whereas $U(l)$ considered in the previous section is a sawtooth potential applied for generating the rectified drift.) and $i(l, t)$ is current at a point l and time t . In a non-uniform transmission line, per-unit length parameters are a function of the position variable [20]. Therefore the distributed resistance, capacitance and inductance at any point l can be expressed as $r_s = r_s(l)$ $C_s = C_s(l)$, $\lambda_s = \lambda_s(l)$ respectively. After applying Kirchoff's voltage law and current law in the inner loop of the lossy transmission line segment shown in Fig. 1, we obtain the following equations:

$$\phi(l + \Delta l, t) - \phi(l, t) = -\Delta l r_s(l) i(l, t) - \Delta l \lambda_s(l) \frac{\partial i(l, t)}{\partial t}, \quad (7)$$

$$i(l + \Delta l, t) - i(l, t) = -\Delta l C_s(l) \frac{\partial \phi(l, t)}{\partial t}, \quad (8)$$

further dividing (7) and (8) with Δl , and taking limits ($\Delta l \rightarrow 0$) yields (9) and (10) respectively:

$$\frac{\partial \phi(l, t)}{\partial l} = -r_s(l) i(l, t) - \lambda_s(l) \frac{\partial i(l, t)}{\partial t}. \quad (9)$$

$$\frac{\partial i(l, t)}{\partial l} = -C_s \frac{\partial \phi(l, t)}{\partial t}. \quad (10)$$

Differentiating (9) with respect to l and (10) with respect to t and in addition to above, with mathematical operations and substitutions (for details refer [23]) the differential equation

for voltage on a lossy transmission line is obtained as:

$$\begin{aligned} \frac{\partial \phi(l, t)}{\partial t} &= \frac{\partial}{\partial l} \left(\frac{1}{r_s(l)C_s(l)} \frac{\partial \phi(l, t)}{\partial l} \right) \\ &- \frac{1}{r_s(l)} \frac{\partial}{\partial l} \left(\frac{1}{C_s(l)} \right) \frac{\partial \phi(l, t)}{\partial l} - \frac{\lambda_s(l)}{r_s(l)} \frac{\partial^2 \phi(l, t)}{\partial t^2} \\ &+ \left(\frac{\partial}{\partial l} \left(\frac{\lambda_s(l)}{r_s(l)C_s(l)} \right) - \frac{\partial}{\partial l} \left(\frac{1}{C_s(l)} \right) \left(\frac{\lambda_s(l)}{r_s(l)} \right) \right) \frac{\partial i(l, t)}{\partial t}. \end{aligned} \quad (11)$$

As the system approaches the steady state, the 3rd and the 4th terms of (11) can be neglected. Now (11) can be rewritten as:

$$\begin{aligned} \frac{\partial \phi(l, t)}{\partial t} &= \frac{\partial}{\partial l} \left(\frac{1}{r_s(l)C_s(l)} \frac{\partial \phi(l, t)}{\partial l} \right) \\ &- \frac{1}{r_s(l)} \frac{\partial}{\partial l} \left(\frac{1}{C_s(l)} \right) \frac{\partial \phi(l, t)}{\partial l}, \\ \text{Or} \\ \frac{\partial \phi(l, t)}{\partial t} &= \frac{\partial}{\partial l} \left(D \frac{\partial \phi(l, t)}{\partial l} \right) - v_p \frac{\partial \phi(l, t)}{\partial l}. \end{aligned} \quad (12)$$

The above (12) is clearly equivalent to (6); thus, on comparing (6) and (12), we can express the diffusion coefficient and propagation velocity in terms of transmission line parameters, as shown below:

$$D(l) = 1/(r_s(l)C_s(l)), \quad (13)$$

$$v_p = \frac{1}{r_s(l)} \frac{\partial}{\partial l} \left(\frac{1}{C_s(l)} \right). \quad (14)$$

Assuming $D(l) = D$ to be constant throughout the channel. we substitute (5) and (13) in (14), on solving for conditions $C_s(0) = C_0$ and $C_s(l) = C$, where C_0 is the initial capacitance:

$$\int_0^l \frac{ql}{Dt_c} \partial l = \int_{C_s(0)=C_0}^{C_s(l)=C} \frac{1}{C_s(l)} \partial C_s(l), \quad (15)$$

we obtain capacitance and resistance as an exponential function of l and v_p as:

$$C = C_0 \exp\left(\frac{v_p l}{D}\right), \quad (16)$$

$$r_s(l) = \frac{1}{C_0 D} \exp\left(-\frac{v_p l}{D}\right). \quad (17)$$

Modeling of a non-uniform lossy transmission line is possible by replacing it with the lossless transmission line segment of length Δl between two consecutive nodes [26]. Various schemes are possible for solving the network shown in Fig. 1, however, the simplest and most suited model for this application is the link-line transmission model [26], [27], as presented in Fig. 6. In the link-line transmission model nodes m and $m + 1$ are placed between lumped resistors r_{ab} connected through a transmission line impedance (i.e., characteristic impedance). The link-line transmission model acts as a delay line so that the signal incident at one node arrives at the other node with some constant delay. Correspondingly any two consecutive nodes of the link line are the two consecutive electrodes of the DEP relay-assisted MC system. The delay in propagation of the signal from one node to the next node

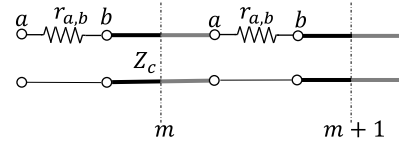


FIGURE 6. The link-line configuration of a transmission model.

corresponds to the propagation time from one relay to the next relay. The propagation velocity (v_p) and the characteristic impedance (Z_c) of a lossless transmission line is expressed as [20]:

$$v_p = 1/\sqrt{\lambda_s(l)C_s(l)}, \quad (18)$$

$$Z_c = \sqrt{\lambda_s(l)/C_s(l)}. \quad (19)$$

Z_c further can be expressed as below by substituting the values of $\lambda_s(l)$ and $C_s(l)$:

$$Z_c = \frac{1}{C_0 v_p} \exp\left(-\frac{v_p l}{D}\right). \quad (20)$$

The other important parameters of the transmission line are the reflection coefficient and the transmission coefficient. When the incident voltage wave encounters the impedance discontinuity at the node, only a fraction of the incident voltage wave is transmitted forward. This fraction is termed as the transmission coefficient (Γ_t). The remaining fraction of the voltage wave is reflected back to the originating node that is termed as a reflection coefficient of $\Gamma_r = (1 - \Gamma_t)$. If link resistor $r_{a,b} = r_s(l)$ for the segment shown in Fig. 6, then Γ_t at the resistor $r_s(l)$ is expressed as [26]:

$$\Gamma_t = 2Z_c/(r_s(l) + 2Z_c), \quad (21)$$

and reflection coefficient at the resistor $r_s(l)$ can be written as:

$$\Gamma_r = r_s(l)/(r_s(l) + 2Z_c) \quad (22)$$

As discussed earlier, it is essential to maintain the signal strength above a threshold value at the receiver in a concentration encoding process. The transmission coefficient is an important parameter in the determination of signal strength at any node. In the DEP assisted molecular communication system, the Γ_t corresponds to the probability of molecules moving forward, while $\Gamma_r = (1 - \Gamma_t)$ is equivalent to $(1 - q)$ i.e., probability of backward diffusion. Furthermore, if Γ_t is increased (i.e., backward diffusion decreases) then, chances of interaction between current and previously transmitted signal is reduced, thus reducing the effect of inter symbol interference.

IV. PULSE PROPAGATION IN MICROFLUIDIC CHANNEL

In this section, we model how a pulse propagates in a microfluidic channel without DEP force. We also model the temporal spreading and attenuation of the concentration signal when it is subjected to a frequency dependent attenuation. We consider a point transmitter releasing ($N\delta t$) molecules in

to the channel, at $t = 0$. Thus, the concentration $c(l)$ at any point l can be expressed as:

$$c(l) = \frac{N}{\sigma\sqrt{2\pi}} \exp\left(-\frac{l^2}{2\sigma^2}\right), \quad (23)$$

where $\sigma = \sqrt{2Dt_{off}}$, (23) is Fourier transformed with respect to spatial parameter l , which is also a Gaussian function and can be expressed as:

$$c(k) = N_k \exp\left(-\frac{1}{2}k^2\sigma^2\right), \quad (24)$$

where k is wave number and defined as $k = 2\pi\nu$, where ν is spatial frequency $\nu = \frac{1}{\Lambda}$ and Λ is wavelength. Wave number of spatial frequency is converted to angular frequency ω of temporal frequency as $k = \frac{\omega}{v_p}$, (24) is rewritten as:

$$c(\omega) = N_\omega \exp\left(-\frac{1}{2}\omega^2\sigma_{v_p}^2\right), \quad (25)$$

where $\sigma_{v_p} = \frac{\sigma}{v_p}$. It is shown in [28] that the attenuation inside a microfluidic channel is also frequency dependent, so we multiply the (25) by frequency dependent attenuation:

$$c_A(\omega) = N_\omega \exp\left(-\frac{1}{2}\omega^2\sigma_{v_p}^2\right) \exp(-\omega\beta l), \quad (26)$$

where β is the attenuation factor and is defined as:

$$\beta = r_s(l)/2Z_c. \quad (27)$$

Now transforming (26) to time domain, we obtain the attenuated and deformed waveform in time domain and is expressed as:

$$c_A(t) = \frac{N}{\sigma\sqrt{2\pi}} [\exp(a^2) \operatorname{erfc}(a) + \exp(b^2) \operatorname{erfc}(b)], \quad (28)$$

where $a = \frac{\beta l - jt}{2\sigma_{v_p}}$, $b = \frac{\beta l + jt}{2\sigma_{v_p}}$. The peak concentration value can be obtained by setting $t = 0$.

$$c_p(l) = \frac{2N}{\sigma\sqrt{2\pi}} \exp\left(\frac{\beta l v_p}{2\sigma}\right)^2 \operatorname{erfc}\left(\frac{\beta l v_p}{\sigma}\right). \quad (29)$$

In pulse propagation without DEP assisted relay MC, the attenuated waveform is a function of the distance propagated and attenuation constant. We observe that the attenuated waveform is not Gaussian, and as it propagates further in length through the channel, it will lose energy and bandwidth both. However, in the DEP relay-assisted MC system, the distance between T_l and R_l is divided amongst electrode, and each electrode acts as a buffer and a relay. Therefore, the molecules are collected and buffered by electrode during t_{on} time, and are diffused towards next electrode in t_{off} time [11]. As discussed in the previous section, the DEP relay-assisted MC system helps in maintaining the Gaussian waveform, which in turn helps in maintaining received signal strength at the R_l .

A. TRANSFER FUNCTION

We obtain the transfer function of an inter relay segment of length l (i.e., the length between two electrodes) of the microfluidic channel during t_{off} . Since (6) defines the propagation of concentration, we substitute (13, 14) and $v_p = 1/\sqrt{\lambda_s(l)C_s(l)}$ in (6), and obtain following differential equation:

$$\frac{\partial c(l, t)}{\partial t} = \frac{1}{r_s(l)C_s(l)} \frac{\partial^2 c(l, t)}{\partial l^2} - \frac{1}{\sqrt{\lambda_s(l)C_s(l)}} \frac{\partial c(l, t)}{\partial l}. \quad (30)$$

Taking Fourier transform of (30) we get:

$$j\omega c = \frac{1}{r_s(l)C_s(l)} \frac{\partial^2 c(l, \omega)}{\partial l^2} - \frac{1}{\sqrt{\lambda_s(l)C_s(l)}} \frac{\partial c(l, \omega)}{\partial l}. \quad (31)$$

Solving the above ordinary differential equation in frequency domain with suitable boundary conditions $c(0, j\omega) = 1$; $c(\infty, j\omega) = 0$, we obtain a transfer function as:

$$S(l, \omega) = \exp\left(-lr_s(l)\sqrt{\frac{C_s(l)}{\lambda_s(l)}}\left(1 - \sqrt{1 + \frac{4j\omega\lambda_s(l)}{r_s(l)}}\right)\right). \quad (32)$$

Taylor expansion of this equation yields an approximated transfer function which is expressed as:

$$S(l, \omega) = \exp\left(-lr_s(l)\sqrt{\frac{C_s(l)}{\lambda_s(l)}}\left(\left(\frac{\omega\lambda_s(l)}{r_s(l)}\right)^2 + j\frac{\omega\lambda_s(l)}{r_s(l)}\right)\right). \quad (33)$$

Using (27), (33) and $k = \omega/v_p$ we obtain spatial frequency dependent transfer function which is written as:

$$S(l, k) = \exp\left(-l\beta\left(\frac{k^2\lambda_s(l)}{r_s^2(l)C_s(l)} + j\frac{k\sqrt{\lambda_s(l)}}{r_s(l)\sqrt{C_s(l)}}\right)\right). \quad (34)$$

The above transfer function is the frequency response of molecule concentration diffusing in the inter relay segment of length l during time t_{off} .

V. NUMERICAL RESULTS

In this section, we present the results of the DEP relay-assisted MC system modeled as a transmission line. Specifically, we have observed the role of relays in attenuation of the signal. Numerical investigation has been carried out for following parameters: electrode length $d_1 = 2.5\mu\text{m}$, probability of molecule moving forward q is set to 0.5, considering no backward diffusion, diffusion coefficient $D = 75\mu\text{m}^2/\text{sec}$ and t_{on}, t_{off} are taken as 30s and 8 s respectively. The following parameters are evaluated: per unit length resistance, capacitance, inductance are evaluated for varying distance $l = (d_1 + d_2)$ ranging from $2.5\mu\text{m}$ to $100\mu\text{m}$. Characteristic impedance and attenuation constant for the lossy transmission line are also evaluated. Fig. 7 shows the Gaussian input concentration propagation in lossy transmission line when subjected to a frequency dependent attenuation for varying distance. It shows that as the pulse propagates down the lossy transmission line, it loses high frequency energy, which results in a reduction of the bandwidth. It can be observed in the result that the peak concentration reduces significantly with the increase in distance. However, if DEP electrodes are

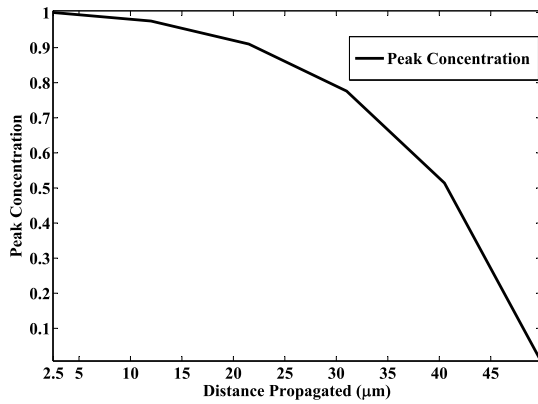


FIGURE 7. Peak concentration versus distance propagated by a Gaussian input Concentration.

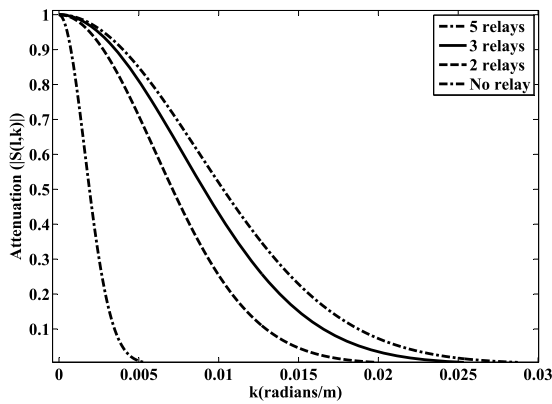


FIGURE 8. Attenuation for varying number of relays versus spatial frequency.

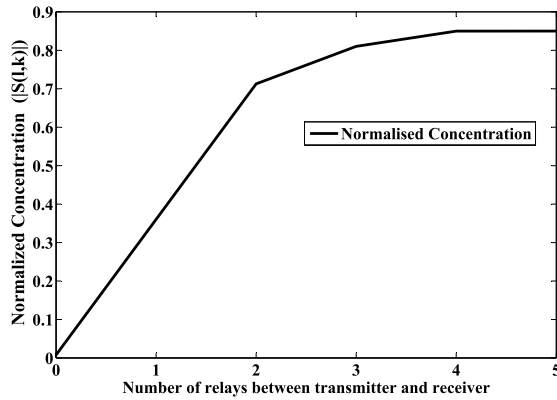


FIGURE 9. Effect of relays on normalized concentration of molecules.

placed in the channel, each electrode will act as a buffer in t_{on} cycle (i.e., collect molecules) and subsequently in t_{off} it will relay molecules to the adjacent electrode. Therefore such a system will help in maintaining sufficient signal strength at the receiver. Thus, the DEP relays assisted the MC system has less attenuation and, as a result, less reduction in bandwidth, compared to the MC system without relays.

Velocity is proportional to the distance between two relays, and therefore, the delay increases with the increase in the number of relays. Fig. 8 shows that spatial frequency

increases, and attenuation decrease with a higher number of relays. From Fig. 8 it can be seen that for concentration to reach 50 percent, the spatial frequency of the 5-relay system is nearly 5.5 times higher than a no-relay system. For a 3-relay system, it is about five times higher than a no-relay system. Thus, when relays are increased from 3 to 5, the gain is marginal. Therefore, it can be inferred that the number of relays can be optimized, and transmission of low frequency concentration signal can be done with less attenuation by using DEP relay-assisted MC. The total length of micro-channel is taken to be $100\mu\text{m}$, which is subsequently divided into 2 to 5 relays, which are equally spaced. Fig. 9 shows the effect of relays on the normalized concentration of molecules. As the concentration propagates through the channel, it gets attenuated. We observe that the attenuation in concentration reduces as the number of relays is increased. Furthermore, it is observed that on increasing relays from 3 to 5, there is no significant reduction in attenuation.

VI. CONCLUSION

This paper proposes the modeling and characterization of the DEP relay-assisted MC system using the transmission line technique. Here we use the transmission line technique in evaluating the reflection and transmission coefficient, which can be used in determining signal strength at any node. We analytically derive the concentration profile of a molecule after a certain time t . We also derive the transfer function of the inter relay segment of the DEP relay-assisted MC system during t_{off} period. Numerical results show that peak concentration value decreases when the signal is subjected to frequency dependent attenuation; thus, the signal loses high frequency energy and bandwidth. Moreover, the numerical simulation shows that incorporating DEP relays in MFC reduces attenuation, i.e., an increase in relays reduces attenuation. However, the number of relays can be optimized. Furthermore, it can be inferred that the DEP relay-assisted MC system can enable transmission of low frequency signal with low attenuation. The results obtained are consistent with those obtained with already existing techniques. Thus, the transmission line technique can be utilized for characterizing a microfluidic system for molecular communication.

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