A Fractal-Tree Channel Model for Touchable Molecular Communication over Blood Vessels

Yu Zhou, Lujiang Qian, Yifan Chen, Rui Wang, and Qingfeng Zhang
Department of Electrical and Electronic Engineering
South University of Science and Technology of China, Shenzhen, China

***Abstract*—Recent progress on bioresorbable and biocompatible miniature systems provides prospect for developing novel nanobots working inside the human body. These small-scale systems are expected to dissolve *in vivo* and cause no side-effect after completing their tasks. In this paper, we propose a fractal-tree channel model for touchable molecular communication (TouchCom) over the vascular network, which utilizes physically transient nanobots as vehicles for targeted delivery of drug particles. More specifically, we generate the structure of arterial systems by using fractal trees and analyze the propagation behavior of nanobots in the blood vessels. Subsequently, the performance metrics of propagation delay and path loss can be derived by using the proposed channel model.**

I. Introduction

Emerging semiconductor materials exhibiting transient behavior and biodegradable engineered bacteria [1], combined with nanorobotic technologies [2], may find important applications in the medical field. These inorganic or organic miniature robots will physically disappear in the human body after completing the required tasks and cause no harm. It is envisaged that the biodegradable nanorobotic systems will continue evolving for *in vivo* applications, especially in the use of drug delivery [3].

Motivated by these emerging technologies, we propose to employ a cross-scale transient nanorobotic platform for transporting a pharmaceutical compound in the human body. The proposed system includes an external macro-unit (MAU) and a number of *in vivo*, drug-loaded nanobots, which may be in the form of biodegradable silicon-based electronics [1] or engineered bacteria [2]. As shown in Fig. 1, the MAU directs the movement of a swarm of nanobots by generating a guiding field [3]. The MAU also applies angiography to visualize partially the inside, or lumen, of blood vessels in the human body. For tracking of the swarm, the drug cargo may be labeled with fluorescent carbon nanotubes or quantum dots. From a touchable molecular communication (TouchCom) perspective, nanobots and cargo are message carriers, blood vessels are the channel for information exchange, and the loading and unloading of cargo correspond to the transmitting and receiving processes, respectively. The term "touchable" in TouchCom represents that the communication process can be controlled and tracked. This is similar to controlling through simple or multi-touch gestures by touching the screen with a finger through a touchscreen, where the "finger" here refers to the external propulsion-and-steering gradient [3].

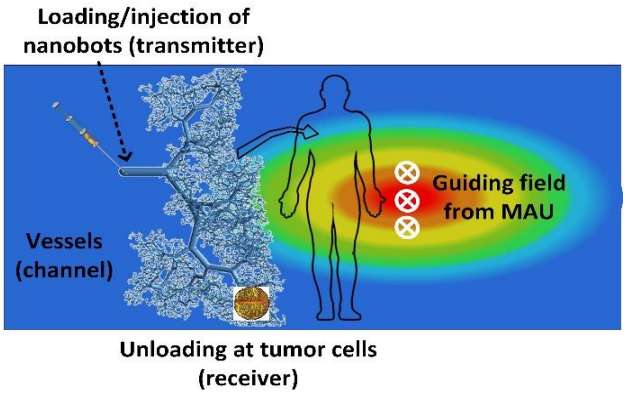

Fig. 1. Conceptual illustration of the TouchCom system.

This paper provides a channel model for the TouchCom system, which incorporates the vascular morphology, the speed of nanobots based on the blood flow analysis, and the key performance metrics of propagation delay and path loss.

II. Modeling Methodology

A. Vascular Model

In order to synthesize the movement of a nanobot swarm in the blood vessels, a model to characterize the vascular network should be constructed. Vasculature in the human body exhibits successive dichotomous division, or bifurcation. The self-similarity of bifurcation gives the vascular connection a fractal character, which could be described by the Murray's law as detailed in [3].

B. Speed of Blood Flow

From the mechanic's point-of-view, the human circulatory system could be treated as a set of complex enclosed pipelines. As such, the Poiseuille's law can be applied to analyze the circulation system and explore the blood flow characteristics [4]:

$$Q = \frac{\pi R^4}{8\mu}\frac{\Delta P}{L} \text{ and } v_x(t) = \frac{1}{4\mu}\frac{\Delta P}{L}[R^2 - r^2(t)],$$

where Q is the blood flow volume, μ is the viscosity of the blood, ΔP is the difference of blood pressure at the two ends, R and L are the radius and length of the vascular pipe, respectively, $r(t)$ is the distance between the swarm and the center line of the vessel at propagation time t, and $v_x(t)$ is the horizontal component of the blood velocity at time t.

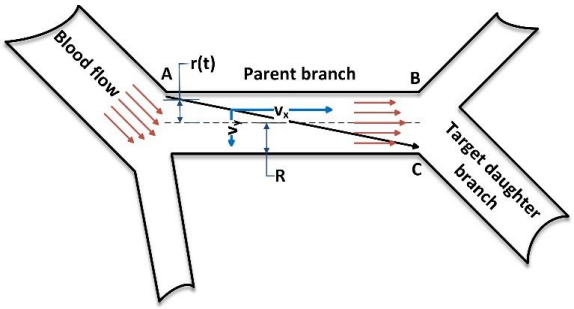

Fig. 2. Movement and velocity of nanobot swarm between two bifurcations.

Suppose that the size of a swarm is much smaller than the diameters of large vessels, the swarm can be treated as a point in the vessel. Then its motion between two bifurcations can be categorized into two different scenarios as shown in Fig. 2:

*1) Lateral Movement (From **A** to **B**)*

In this case, the swarm swims along the same side of the vessel. Only the horizontal component of the velocity v_x contributes to the propagation delay.

*2) Diagonal Movement (From **A** to **D**)*

In this case, the swarm travels across the parent branch and enters the target daughter branch on the opposite side. Thus, a constant vertical component of the velocity v_y caused by the external guiding field is included besides v_x.

C. Path Loss

In TouchCom, the classical channel model parameter of path loss is employed to describe the amount of drug particles successfully reaching the targeted site. It is given by the average percentage of nanobots delivered to the tumor cells over multiple realizations of the drug delivery process, which is dependent on the branching lost incurring at the distal ends of the vascular tree. This microvasculature may become too slender to be imaged through angiography. Thus, the guiding field only provides a gradient pointing towards the destination. Define β_1 and β_2 to be the angles between the guiding field towards the targeted site and the two daughter branches at a bifurcation. The probabilities for the nanobot swarm to enter the two branches, p_1 and p_2, are assumed to be proportional to the difference of the two angles, $\Delta\beta = \beta_2 - \beta_1$ [5]:

$$p_1 = 50\% \times \left(1 + \frac{\Delta\beta}{\beta_1+\beta_2}\right) \text{ and } p_2 = 1 - p_2.$$

III. Simulation Results

Based on the aforementioned methodology, a series of simulations have been performed, including the fractal vascular network, the propagation delay, and the path loss. Fig. 3(a) presents the structure of a typical vascular network. The root vessels of all the trees have the same diameter of 1 mm. The diameters of daughter branches reduce up to 30% at every bifurcation. For a 10-level network, the vessel ends at a diameter of below 10 μm, which is close to the average value of capillaries. The plasma viscosity μ is set to be 229 mPa/s and the pressure difference ΔP is in the range of 100~200Pa. For an 'n'-level network, totally we have 2^n ends. Every end corresponds to a targeting route from the injection site. It is assumed that the tumor cells may locate at any of these ends. Fig. 3(b) presents the distribution of the propagation delay for vascular trees with different depths (levels).

Fig. 4(a) presents the average propagation delay for vascular trees with different depths. Each level introduces an additional delay in the range of $40 - 140$ s; the variation is due to the fact that for certain vessel segments the nanobot swarm has undergone longer diagonal movement; the delivery time is more than 10 min if the vascular tree has more than 8 levels. Fig. 4(b) presents final concentration of nanobots swarm for different angiographical resolutions. It is evident that the imaging quality has a significant influence on the path loss. Each additional level of unresolvable vessels will bring about 20% lost on average.

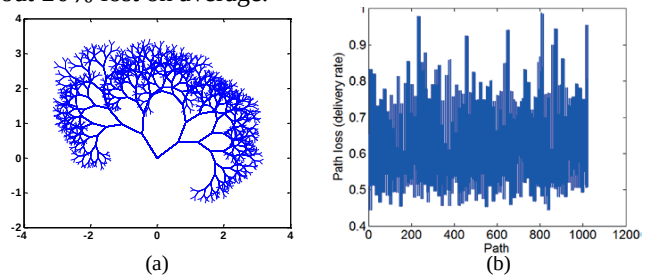

Fig. 3. (a) Fractal-based vascular network with 10 levels, and (b) propagation delay distribution over 1000 independent simulations of the vasculature.

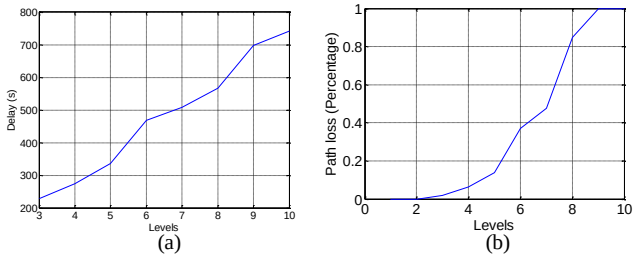

Fig. 4. (a) Average propagation delay for vascular trees with different levels. (b) The final concentration of nanobots for different angiographical resolutions; the *x*-axis denotes the number of angiographically unresolvable levels.

Acknowledgment

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