

# Preface

Molecular communication is one of the oldest and the most pervasive communication mechanisms on Earth. It is essential for all living entities from unicellular organisms to multicellular animals and plants to retain their vital functionalities. For example, many bacteria respond to signaling molecules which are secreted by their neighbors. This process, called quorum sensing, enables bacteria to coordinate their behavior, including their motility, antibiotic production, spore formation, and sexual conjugation. Signaling molecules (e.g., pheromone) are also extensively used by a great variety of animal species ranging from insects to higher primates to transmit and receive information for many behavioral functions. For example, pheromones may be released by an individual for directing others to suitable food sites or for informing others about the existence of a predator, or for a variety of other behavioral functions. Furthermore, cells communicate using signaling molecules to make a multicellular organism (e.g., human). For example, in neuronal system, electrical impulses (i.e., action potential) and neurotransmitters (i.e., signaling molecules) are jointly used by neuron cells to communicate with target cells. In endocrine system, endocrine cells release hormone molecules (i.e., signaling molecules) into the blood stream to communicate with distant target cells. Furthermore, gap junction channels enable adjacent cells to communicate using small intracellular signaling molecules (e.g., calcium) and such gap junctional communication of cells regulates so many cellular processes.

Besides these fascinating molecular communication mechanisms in nature, developments in nano- and biotechnology have recently revealed that molecular communication is also a promising alternative for the interconnection of very tiny “biomimetic machines” or commonly known as nanomachines such as engineered cells and bionanorobots. The interconnection of these nanomachines, i.e., nanonetwork, is expected to enable sophisticated medical, industrial, and environmental applications. In these applications, molecular communication among nanomachines can enforce reliability and controllability. More importantly, molecular communication can coordinate different nanomachine populations to reach highly sophisticated behavior and increase the number of design possibilities. For example, a group of non-communicating engineered cells behaves asynchronously and cannot

coordinate to perform a predefined task. Communicating engineered cells can overcome the asynchronous behavior problem and coordinate the cell population for a tissue engineering application. Furthermore, molecular communication may be also required in sophisticated applications in order to efficiently gather and correlate sensory inputs for making decision.

In this book, the concepts of molecular communication and nanonetworks are introduced from the viewpoint of communication theory. The book mainly focuses on molecular communication between two nodes called transmitter nanomachine (TN) and receiver nanomachine (RN). Depending on how messenger molecules are guided and transported from the TN to the RN, molecular communications between the TN and RN are categorized into two main types. The first type is called passive molecular communication (PMC) and the second type is called active molecular communication (AMC).

In PMC, molecules passively diffuse from the TN to the RN without any need for an intermediate system which guides and transports the molecules. Depending on how the RN receives messenger molecules, PMC is classified into two types, called as PMC with absorbers and PMC with ligand–receptor binding. In PMC with absorbers, the RN is assumed to be an absorber to take molecules in it whenever they come in contact with its surface. In PMC with ligand–receptor binding, the RN is assumed to have surface receptors to receive molecules in its close proximity by means of ligand–receptor binding mechanism.

In AMC, after molecules are emitted by the TN, they need an intermediate system which guides and transports them to the RN. Four different intermediate systems are identified in AMC. In the first system molecular motors are used to carry molecules from the TN to the RN. In the second system, the TN and RN are assumed to be contacted and gap junction channels between the TN and RN mediate the diffusion of molecules. In the third system, messenger molecules are injected into motile bacteria in the TN and then, the bacteria with messenger molecules move towards the RN by following attractor molecules emitted by the RN. If one of the bacteria reaches the RN, the messenger molecules are received by the RN. Finally, in the fourth system, the TN and RN are assumed to be mobile. Messenger molecules remain to be attached on the surface of the TN. Whenever the TN and RN collide, these messenger molecules and receptors on the surface of the RN interact to deliver information carried by the messenger molecules. The details of PMC and AMC are given throughout this book as follows.

In Chap. 1, the concept of molecular communication and nanonetwork is introduced. The existing and envisioned nanomachines, nanorobots, and genetically engineered machines are first discussed. Then, molecular communication paradigms (including nature-made molecular communication mechanisms) are categorized and briefly mentioned.

In Chap. 2, PMC with absorbers is introduced. Throughout this chapter, the RN is assumed to be an absorber. After the molecule emission process of the TN is discussed, the diffusion of the emitted molecules is elaborated by giving the required details of random walk and diffusion phenomenon. Then, the molecule reception process of the RN is detailed by deriving the reception rate for the RN

and examining the accuracies of concentration and gradient sensing performed by the RN. By incorporating the mathematical models of the emission, diffusion, and reception processes, unified models are introduced for PMC. Finally, communication theories and techniques devised for PMC with absorbers are introduced.

In Chap. 3, PMC with ligand–receptor binding is introduced. Throughout this chapter, the RN is assumed to have surface receptors to receive molecules in its close proximity by means of ligand–receptor binding mechanism. The deterministic and probabilistic models of the ligand–receptor binding are first introduced. Then, PMC in gene regulatory networks is discussed and a unified model incorporating the diffusion of molecules and ligand–receptor binding is introduced. Accuracies of the concentration and gradient sensing with ligand–receptor binding are also investigated. Finally, the communication theories and techniques are given for PMC with ligand–receptor binding.

In Chap. 4, AMC with four different intermediate systems is introduced. AMC with molecular motors is first presented by discussing the physics of motor proteins used for cargo transport in living cells. Then, by discussing the intercellular signaling with gap junction channels, AMC with gap junction channels is introduced for contacted nanomachines. Then, motile behavior of bacteria is discussed and the concept of AMC with motile bacteria is introduced. Finally, based on contact-dependent intercellular signaling, AMC among mobile nanomachines is introduced.

**Acknowledgments** I thank my wife and my son since they give me a great motivation. I am also deeply indebted to my wife for her endless love. I would also like to express my sincere gratitude to my parents, my mother-in-law and father-in-law, my brother, and my sister for their endless support.

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<http://www.springer.com/978-1-4939-0738-0>

Molecular Communications and Nanonetworks

From Nature To Practical Systems

Atakan, B.

2014, XIII, 184 p. 74 illus., 3 illus. in color., Hardcover

ISBN: 978-1-4939-0738-0