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MOLECULAR COMMUNICATION: Interconnecting Tiny NanoBio Devices

Recent advances in the fields of bioengineering and nanotechnology have resulted in the emergence of tiny devices of sub-millimeter and even micron or less dimensions that can perform sensing and actuation. In many cases, the main challenge in moving these devices out of the laboratory and into the real world is not production cost, as they can be produced cost-effectively in large volumes, but rather a communication problem. For many applications, these tiny devices need to communicate and collaborate in swarms, or they need to transmit their measurements to other devices. Inspired by nature, chemical signaling (also known as molecular communication) is an effective solution to this problem. This article explores some of the recent advancements and challenges in engineering molecular communication systems.

The idea of small devices swimming in the body to find and destroy various pathogens to cure diseases has been around for a few decades and was perhaps well popularized by the 1966 film *Fantastic Voyage*. Over the past decade, with the advancements in the field of biology, bioengineering, and nanotechnology, sub-millimeter devices are beginning to emerge, not only for applications in medicine, but also other applications, such as environmental cleaning and manufacturing [1], [2], as well as data storage on molecular structures (e.g., DNA storage). Therefore, it is not surprising that the 2016 Nobel Prize in chemistry was awarded "for the design and synthesis of molecular machines."

For many applications, especially in medicine, synthetic biology is used to create a perfectly self-sufficient micro/nano-sized device based on a genetically modified cell [3], [4]. This is in part because of the biocompatibility of synthetic biological devices. In humans, for example, there are at least as many bacterial cells living inside the body as there are human cells [5]. These helpful bacteria regulate many functions of the body, and many different diseases have been linked to imbalances in the human microbiome [6]. Another important benefit in using synthetic biological devices is that it would be much easier to reprogram cells rather than to design and build completely new machinery for micro/nano-sized robots that can perform sensing and actuation in the body. Some recent examples of biosynthetic devices include genetically modified bacteria that can be used to detect cancer cells in vivo [7], [8], and bacteria that can be used for targeted drug delivery [9].

It is also possible to design and build sub-millimeter devices using novel materials, such as graphene. For example, in [10] a micro-sized device based on graphene is developed, which could potentially be used for removal of nano-sized toxic contaminants

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from lakes and rivers, while in [11] a micro-sized chemically propelled fishlike structure is 3D-printed. These devices can be used in applications ranging from environmental cleaning to manufacturing and infra-structure monitoring.

For many of these envisioned applications, the main challenge in moving sub-millimeter devices out of the laboratory and into the real world is not production cost, as they can be produced cost-effectively in large volumes (e.g., using 3D-printing or bacteria that simply multiply on their own). One of the main challenges is rather a communication problem. Today, modern telecommunication systems, which use electrical or electromagnetic (EM) signals (from radio to optical bands), have changed the world, allowing us to communicate and collaborate in ways that were unimaginable just a few decades ago. However, simply shrinking the size of an EM system to micro and nano dimensions is very challenging because of constraints, such as the ratio of the antenna size to the wavelength of the electromagnetic signal [12], [13]. Optical communication is also not suitable for many applications since it requires either a guided medium (e.g. fiber optical cable) or line of sight. Some of the other constraints that further limit the use of EM technology are energy efficiency and bio-compatibility, which are important for many practical applications, especially in synthetic biology and medicine.

Inspired by nature, one possible solution to these problems is to use *chemical signals* as carriers of information, which is called *molecular communication* [14], [15]. In molecular communication, a transmitter releases small particles, such as molecules or lipid vesicles, into an aqueous or gaseous medium, where the particles propagate until they arrive at a receiver. The receiver then detects and decodes the information encoded in these particles. In nature, chemical signals are used for inter-cellular and intra-cellular communication at microscales and nanoscales [16], while pheromones are used for long-range communication between members of the same species, such as social insects [17]. Therefore, chemical signals can be used for communication at both macroscopic and microscopic scales, and tend to be biocompatible.

Another benefit of these systems is that molecules can often be the most energy-efficient means of communication when delay can be tolerated. They can also store tremendous amounts of information in a small volume. In fact, a once-popular communication networks textbook [18] contains the passage: "Never underestimate the bandwidth of a station wagon full of tapes hurtling down the highway." (A.S. Tanenbaum, *Computer Networks*, 4th ed., p. 91). A good example of this somewhat tongue-in-cheek "folklore" is the DNA and RNA molecules that can encode the entire replication instructions of a virus in a small protein capsule ("station wagon"), tens of nanometer in diameter. The capsule stochastically floats in the environment ("hurtles") until it finds a host cell.

Despite the prevalence of chemical signaling in nature, it was only over the past two decades that biologists and bioengineers have uncovered some of the underlying pathways, and developed techniques for modifying them [19], [20]. Beside this biological approach, molecular communication systems can be viewed from a communication engineering lens [14], [15], [21], [22], where other aspects, such as reliability, data rate, and network protocols are designed and built into these systems to ensure that tiny devices could communicate and collaborate reliably in large swarms. Such an approach is required for transitioning from a few sub-millimeter devices in laboratories to swarms operating in real-world applications [23]. Molecular communication is also important in the design of bio-chips, where components within a chip, such as a DNA storage unit and a molecular processing unit, are connected by chemical signaling. Driven by these applications, it was almost only a decade ago when communication engineers started to slowly investigate this problem [21].

Two important applications that have been the main source of motivation for studying molecular communication systems from a communication engineering perspective are depicted in Figure 1. On the left, data that is encoded in molecular structures, such as DNA sequences or long polymer chains, are "read" by a molecular processing unit, and new data is "written" to the storage unit. The reading and the writing process, which can be modeled

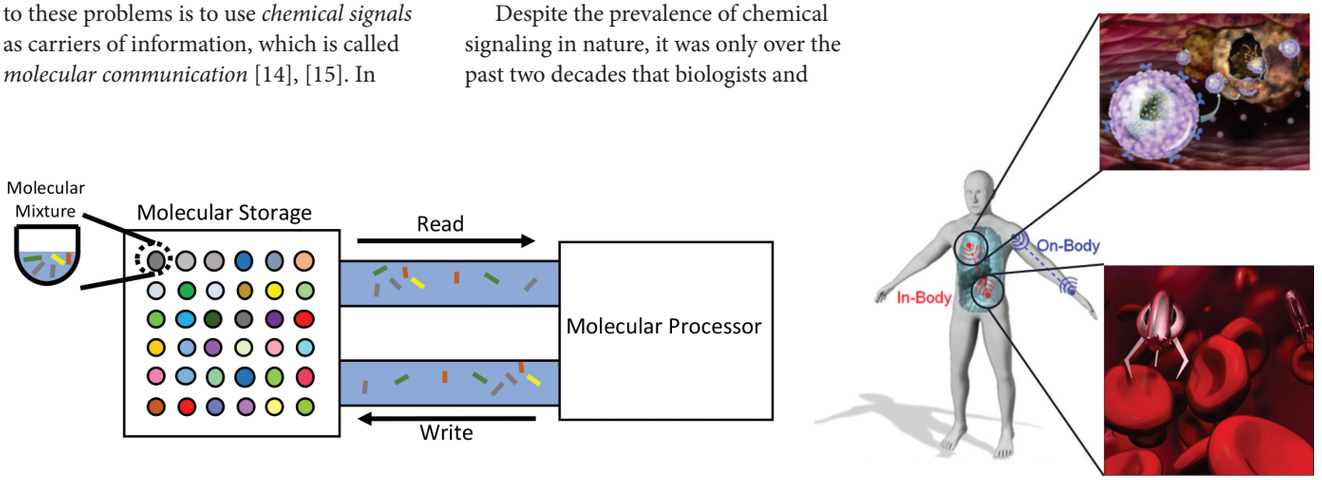

FIGURE 1. Two important applications of molecular communication. Left: Molecular communication for bio-chips can enable molecular storage and molecular processing. Right: An Internet of nano-bio things can be developed using molecular communication enabling real-time in-body diagnostics and treatment.

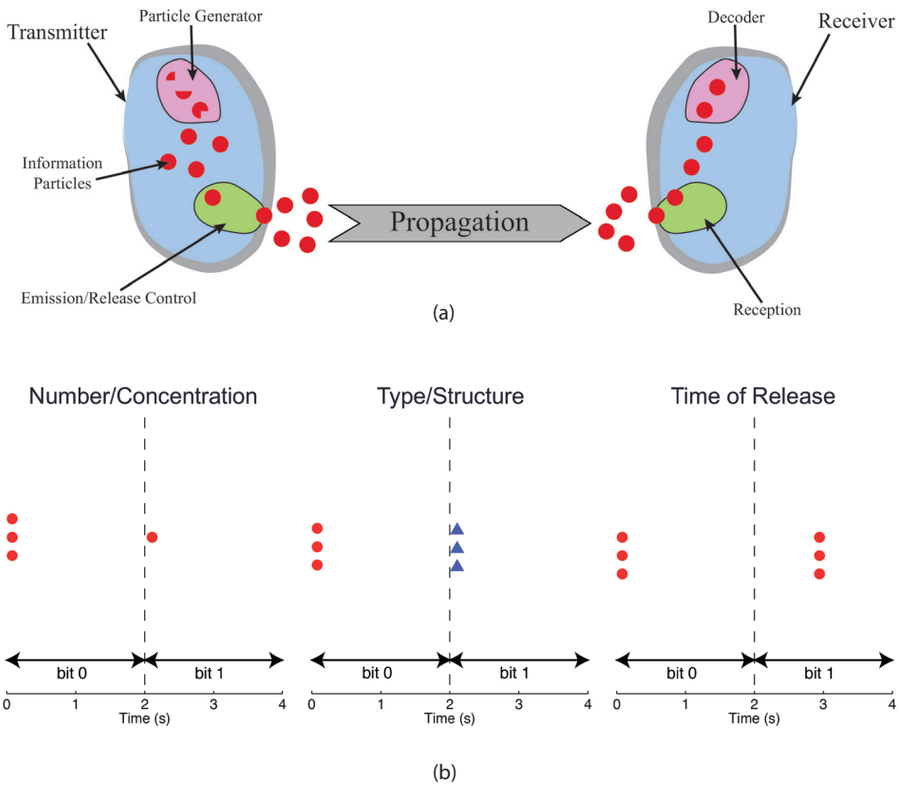

FIGURE 2. An overview of molecular communication. (a) Information is encoded in the particles that are generated and released by the transmitter. The particles are transported from the transmitter to receiver using flow, diffusion or some other random process. The particles that arrive at the receiver are used to decode the information. (b) Information can be encoded in the concentration or number of particles released, in their type or structure, or in the time of release.

as a molecular communication channel, must be designed to be high-throughput and reliable. On the right, tiny devices injected in the body, such as nanorobots or synthetic bacteria, communicate using chemical signaling to enable real-time health monitoring or to find and destroy pathogens.

Although molecular communication is in its infancy, with these seemingly futuristic application plans currently out of reach (i.e., in vivo biological signaling, surgical/medicinal microbot swarms, process-on-a-chip, etc.), its bio-compatibility factor, theoretical potential storage capacity, and energy efficiencies, especially through media unfriendly to radiation, are of sufficient importance to warrant careful theoretical and engineering consideration. This is the main reason the field has attracted considerable attention very recently [14].

OVERVIEW OF MOLECULAR COMMUNICATIONS

The basic idea of molecular communication is very simple, as depicted in Figure 2(a). The transmitter generates particles (or uses stored particles) to encode information. These particles are typically a few nanometers to a few micrometers in size. They could be biological compounds, such as proteins or DNA molecules, or synthetic compounds, such as gold nanoparticles. Information can be encoded (i.e., modulated) on the particles in different ways as shown in Figure 2(b). First, information can be encoded (i.e., modulated) on the intensity or concentration of particles. For example, bit-0 can be represented by release of 3 particles while bit-1 can be represented by release of 1 particle. Second, the information can be encoded by releasing different types of particles. For example, to transmit bit-1, particles of type A are released and to represent bit-0, particles of type B are released. Note that by using the structure of molecules, a large amount of data can be transmitted in this way. For example, in a 32 base-pair single stranded DNA sequence, there are theoretically 4^{32} different symbols that can be transmitted. Finally, information can be encoded on the time of release of particles. For example, releasing the particles at the beginning of the symbol duration can represent bit-0 and releasing them in the middle of the symbol duration represents bit-1.

The transmitter, therefore, must have a mechanism to control the release of particles. As it is difficult to control this process at a molecular level, the transmitter can be faulty itself. The released information particles traverse some spatial gap to the receiver. The environment between the transmitter and the receiver is an aqueous or a gaseous environment where the tiny information particles can freely propagate. When the particles arrive at the receiver, they are captured and detected, and the information decoded.

There are, of course, many details and variations on the theme. For instance, the "gap" (channel environment) could be a medium through which particles diffuse stochastically, or some form of active transport might be employed [29]. Note that not all of the released particles may arrive at the receiver. This could be due to the propagation scheme itself or because the particles degrade or chemically react with other particles.

The reception and detection process could also be noisy. In the biological case, a typical receptor structure is stereochemically matched to a particular signaling particle/molecule and the kinetics of the binding/unbinding process must be considered as well as the number and density of receptors. Moreover, in many electronic sensors, such as metal oxide gas sensors or glass pH sensors, the detector relies on stochastic diffusion of particles into the sensing layer, which increases the uncertainty of the measurements. To add to the potential complexity, a given receptor may preferentially bind to a given particle, but there may be other different (or identical, but from another source) interfering particles, which also bind to the same receptor.

When one considers networks of molecular transceivers, this sort of "cross talk" or outright interference must be considered.

Another major challenge in molecular communication systems is the inter-symbol interference (ISI) problem. As the transmitter releases particles during each symbol duration, some of these particles may remain in the environment and interfere with future transmissions. This problem worsens with time, as the number of particles remaining in the channel from previous transmissions increases. To overcome this issue, some previous works have considered ISI mitigation techniques based on signal-processing, using multiple types of particles and alternating between them during each channel use, and incorporating enzymes in the propagation environment to degrade the information particles.

All of these different scenarios can be combined to create many different systems, each based on a specific modulation scheme, propagation scheme, receiver and transmitter models and other sets of assumptions. Therefore, it is not surprising that there is a large body of work, each proposing a different model, based on different assumptions, which can yield quite different results [14]. Moreover, the simplifying assumptions, which are made in many works to yield analytical results, have not been validated experimentally. For example, in some previous works, the molecular communication channel is modeled as a linear system. However, in [24] it was demonstrated that an experimental molecular communication platform developed in [25] exhibits nonlinearity.

Another major challenge in molecular communication is that the physical characteristics of the channel are significantly different from wireless channels. For example, even if we assume that the molecular communication system can be well approximated as a linear system, the system response is quite different from the response in the wireless radio channels, which renders techniques, such as Orthogonal frequency-division multiplexing (OFDM), impractical. Therefore, new techniques for channel estimation, detection, and channel equilization must be developed [26]–[29].

THEORETICAL LIMITS AND EXPERIMENTAL IMPLEMENTATIONS

One of the most fundamental aspects of any communication system is the Shannon capacity of the communication channel, which characterizes the maximum theoretical achievable data rates for that channel. Understanding this theoretical limit provides an upper bound on performance as well as intuition that is useful for system design. However, even the "simplest" molecular channel has serious analytic complication for characterizing the channel capacity which cannot be ignored: particle indistinguishability which results in ISI. Which particle emission corresponds to which arrival can be ambiguous. That is particles transmitted in the previous symbol duration may arrive during the current symbol interval, and the receiver cannot differentiate between the interfering particles and current transmissions particles.

Previous works have considered two different approaches to mitigate ISI [30]. First, multiple types of particles that are distinguishable at the receiver can be employed where the transmitter alternates between the particles during each channel use [31]–[33]. However, from an information theoretic perspective, this approach is equivalent to having parallel channels, where the symbol duration for each channel is longer. Another approach has been to use enzymes or multiple reactive chemicals to degrade the information particles that remain in the channel [34], [35]. However, formulating analytical channel models for these systems, such that capacity can be calculated, is challenging. It may also be possible to design information particles that are unstable and degrade over time naturally [36]. Although these techniques can reduce the ISI, it cannot completely eliminate it. Therefore, despite these efforts, any realistic formulation of a molecular channel is an ISI channel, where formulating the channel capacity can be challenging.

To find some analytical formulations for channel capacity, previous works have either assumed that the channel has no ISI, or that it has limited ISI, where bounds on capacity can be derived. With these simplifications, it is shown that the data rate for molecular communication can be from a few bits per seconds to a few thousand bits per second if a single type of particle is used for transmission [37]–[39]. For example, one formulation of molecular channel is the particle intensity channel where information is encoded in the intensity/concentration of the particles released. In this case, it can be shown that the channel can be formulated as the Poisson channel, where for the ISI free point-to-point link, the capacity is upper bounded by [37],

$$C \leq C_{\text{upper}} = \begin{cases} \frac{\varepsilon}{A}(A-\varepsilon)\log\left(\frac{A}{\lambda_0}+1\right) & \varepsilon < \frac{A}{2} \\ \frac{A}{4}\log\left(\frac{A}{\lambda_0}+1\right) & \varepsilon \geq \frac{A}{2} \end{cases},$$

where A is the maximum intensity that can be transmitted, ε is the average transmission intensity, and λ_0 is the noise intensity.

Although the capacity of molecular channels is not large compared to wireless radio channels, it can significantly increase if data is also encoded in the structure of particles, such as a DNA sequence. However, in most applications, achieving high data rates is not required. For example, synthetic bacteria, which are designed to detect biomarkers for diseases inside the body, only need to transmit their measurements to other devices in the body or a device under the skin every day or every few hours. As another example, a few hundred bits per second is enough to synchronize many devices in a swarm.

Since the theoretical limits of molecular communication are derived using many simplifying models, in practice, the achievable data rates could be lower. Therefore, experimental platforms and demonstrators are required to validate the models and to evaluate the achievable data rates. The first molecular communication experimental platform was developed in [25]. The goal of this system was to reliably transmit short messages over a distance of a few meters. This system used an electronically controlled spray as the transmitter, a metal oxide sensor that detects the concentration of alcohol at the receiver, and aerosolized alcohol as the information-carrying chemical. Figure 3 shows this platform. It was demonstrated that information can be encoded on concentration of alcohol (i.e. vodka!) simply by transmitting a bit-1 with a short spray burst and a bit-0 with no spray burst. Using this approach, a data transmission rate of 0.3 bits per seconds

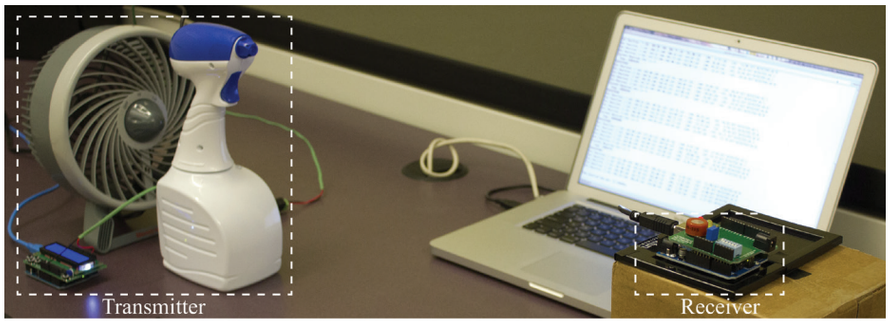

FIGURE 3. First Molecular Communication Platform. The transmitter uses an electronically controlled spray to release alcohol into the environment. The receiver uses a breathalyzer sensor to detect the changes in the concentration of alcohol in the environment.

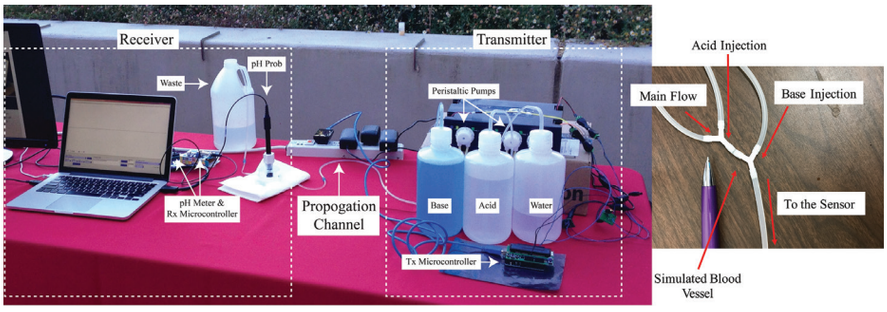

FIGURE 4. Multi-chemical molecular communication system. The transmitter can inject multiple reactive chemicals, such as acids and bases, into a vessel-like environment using peristaltic pumps. The receiver uses a pH probe to detect the changes in the pH level in the environment.

was achieved. Later the platform was extended to a multiple-input multiple-output (MIMO) setup were two spray transmitters and two receiver sensors were used to improve the data rate slightly [40].

The data rate improvement due to MIMO was small, since the multiplexing gain is negligible because of inter-link interference and the ISI that is inherent to molecular communication systems. Theoretically, this can be improved if accurate channel state information (CSI) is known at the transmitter and receiver by subtracting the interferences. Another way to enable possible gains from MIMO as well as to reduce ISI is to use multiple reactive chemicals at the transmitter instead of a single chemical. Such chemical interaction can then be leveraged to design the system such that ISI is reduced. The chemicals can also be chosen such that through reactions, the multiplexing gain that is required for a MIMO setup is improved. To demonstrate this effect, a new platform for multi-chemical communication in vessel-like environments was recently developed [41]. This new platform has two attractive features. First, it simulates an environment that resembles a vein in the body. Second, it uses multiple reactive chemicals to create both constructive and destructive signal superposition. The platform uses peristaltic pumps to inject different chemicals into a main fluid flow in small silicon tubes as shown in Figure 4. Multiple tubes with different diameters can be networked in branches to replicate a more complex environment, such as the cardiovascular system in the body or complex networks of pipes in industrial complexes and city infrastructures. In the platform, there is always a main fluid flow in the tubes, for example, water or blood. Some examples of chemicals that can be injected by the transmitter includes acids and bases, or proteins, carbohydrates and enzymes. The central receiver uses a sensor, such as a pH electrode or a glucose sensor, to detect the chemical signals transmitted by the nodes. Since, in practice, the receiver is a wearable device on/under the skin, it can be more complex, have access to the Internet, and cloud computing platforms. Therefore, it can run a complex detection algorithm.

One simple technique for transmitting information using this platform is through injecting a small amount of base into main flow to represent the bit-1 and injecting a small amount of acid to represent the bit-0. Then at the receiver, one can use a pH electrode to measure the pH level and decode the information. However, the design of a detection algorithm for this system has proved challenging because of difficulties in modeling a molecular communication channel with chemical reactions. Therefore, a data-driven approach was used to train a detection algorithm using techniques from machine learning, which resulted in a system that achieves a data rate of 2-4 bits per seconds [41].

FUTURE CHALLENGES

Molecular communication is still in its infancy and there are many open theoretical problems in the field. For example, the Shannon capacity of a large class of molecular communication channels are still unknown. Despite recent advancement in modeling and simulation of molecular communication systems, good models and simulators for complex communication systems are still unknown. Another important challenge includes validating the mathematical models and the algorithms developed using these models experimentally. Specifically, more work needs to be done on development of experimental platforms that closely resemble real-world environment (e.g., inside the human body). For example, in a recent work, a new experimental setup was developed that demonstrated *in vivo* communication through the earthworm's nervous system [42]. All these interesting open problems and challenges make molecular communication an exciting area of research that can unlock many rewarding and transformative applications. ■

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REFERENCES

[1] R. A. Freitas, *Nanomedicine, Volume I: Basic Capabilities*, 1st ed. Landes Bioscience, 1999.

[2] S. Sengupta, M. E. Ibele, and A. Sen, "Fantastic voyage: Designing self-powered nanorobots," *Angewandte Chemie International Edition*, vol. 51, no. 34, pp. 8434–8445, 2012. http://dx.doi.org/10.1002/anie.201202044

[3] D. Endy, "Foundations for engineering biology," *Nature*, vol. 438, no. 7067, pp. 449–453, 2005.

[4] D. Baker, G. Church, J. Collins, D. Endy, J. Jacobson, J. Keasling, P. Modrich, C. Smolke, and R. Weiss, "Engineering life: Building a fab for biology," *Nature Scientific American*, vol. 294, no. 6, pp. 44–51, 2006.

[5] R. Sender, S. Fuchs, and R. Milo, "Are we really vastly outnumbered? Revisiting the ratio of bacterial to host cells in humans," *Cell*, vol. 164, no. 3, pp. 337–340, 2016.

[6] I. Cho and M. J. Blaser, "The human microbiome: At the interface of health and disease," *Nat Rev Genet*, vol. 13, no. 4, pp. 260–270, Apr. 2012.

[7] T. Danino, A. Prindle, G. A. Kwong, M. Skalak, H. Li, K. Allen, J. Hasty, and S. N. Bhatia, "Programmable probiotics for detection of cancer in urine," *Science Translational Medicine*, vol. 7, no. 289, pp. 289ra84–289ra84, 2015.

[8] J. C. Anderson, E. J. Clarke, A. P. Arkin, and C. A. Voigt, "Environmentally controlled invasion of cancer cells by engineered bacteria," *Journal of Molecular Biology*, vol. 355, no. 4, pp. 619–627, 2006.

[9] S. Martel and M. Mohammadi, "Switching between magnetotactic and aerotactic displacement controls to enhance the efficacy of mc-1 magneto-aerotactic bacteria as cancer-fighting nanorobots," *Micromachines*, vol. 7, no. 6, p. 97, 2016.

[10] D. Vilela, J. Parmar, Y. Zeng, Y. Zhao, and S. Sánchez, "Graphene-based microbots for toxic heavy metal removal and recovery from water," *Nano Letters*, vol. 16, no. 4, pp. 2860–2866, 2016, pMID: 26998896.

[11] W. Zhu, J. Li, Y. J. Leong, I. Rozen, X. Qu, R. Dong, Z. Wu, W. Gao, P. H. Chung, J. Wang, and S. Chen, "3d-printed artificial microfish," *Advanced Materials*, vol. 27, no. 30, pp. 4411–4417, 2015. http://dx.doi.org/10.1002/adma.201501372

[12] H. Wheeler, "Fundamental limitations of small antennas," *Proceedings of the IRE*, vol. 35, no. 12, pp. 1479–1484, Dec. 1947.

[13] C. A. Balanis, *Advanced engineering electromagnetics*, 2nd ed. Wiley, New York, 2012.

[14] N. Farsad, H. B. Yilmaz, A. Eckford, C. B. Chae, and W. Guo, "A comprehensive survey of recent advancements in molecular communication," *IEEE Communications Surveys Tutorials*, vol. 18, no. 3, pp. 1887–1919, thirdquarter 2016.

[15] T. Nakano, A. W. Eckford, and T. Haraguchi, *Molecular Communication*. Cambridge University Press, 2013.

[16] B. Alberts, A. Johnson, J. Lewis, M. Raff, K. Roberts, and P. Walter, *Molecular Biology of the Cell*, 5th ed. Garland Science, Nov. 2007.

[17] W. C. Agosta, *Chemical Communication: The Language of Pheromones*, first edition ed. W H Freeman & Co, Aug. 1992.

[18] A. S. Tannenbaum, *Computer Networks*. Prentice Hall, 2002.

[19] R. Weiss and T. Knight, "Engineered communications for microbial robotics," *DNA Computing, Lecture Notes in Computer Science*, vol. 2054, pp. 1–16, 2001.

[20] C. M. Waters and B. L. Bassler, "Quorum sensing: cell-to-cell communication in bacteria," *Annu. Rev. Cell Dev. Biol.*, vol. 21, pp. 319–346, 2005.

[21] S. Hiyama, Y. Moritani, T. Suda, R. Egashira, A. Enomoto, M. Moore, and T. Nakano, "Molecular communication," in *Proc. of 2005 NSTI Nanotechnology Conference*, 2005, pp. 391–394.

[22] I. F. Akyildiz, F. Brunetti, and C. Blazquez, "Nanonetworks: A new communication paradigm," Computer Networks, vol. 52, no. 12, pp. 2260–2279, August 2008.

[23] P. E. M. Purnick and R. Weiss, "The second wave of synthetic biology: from modules to systems," *Nat. Rev. Mol. Cell Biol.*, vol. 10, no. 6, pp. 410–422, Jun. 2009.

[24] N. Farsad, N.-R. Kim, A.W. Eckford, and C.-B. Chae, "Channel and noise models for nonlinear molecular communication systems," *IEEE Journal on Selected Areas of Communications*, 2014.

[25] N. Farsad, W. Guo, and A. W. Eckford, "Tabletop molecular communication: Text messages through chemical signals," *PLOS ONE*, vol. 8, no. 12, p. e82935, Dec 2013.

[26] D. Kilinc and O. Akan, "Receiver design for molecular communication," *IEEE Journal on Selected Areas in Communications*, vol. 31, no. 12, pp. 705–714, December 2013.

[27] V. Jamali, A. Ahmadzadeh, C. Jardin, H. Sticht, and R. Schober, "Channel estimation for diffusive molecular communications," *IEEE Transactions on Communications*, vol. 64, no. 10, pp. 4238–4252, 2016.

[28] Y. Murin, N. Farsad, M. Chowdhury, and A. Goldsmith, "Time-slotted transmission over molecular timing channels,"*Nano communication networks*, vol. 12, pp. 12–24, 2017.

[29] V. Jamali, N. Farsad, R. Schober, and A. Goldsmith, "Non-coherent detection for diffusive molecular communication systems," *IEEE Transactions on Communications*, vol. PP, no. 99, pp. 1–1, 2018.

[30] B. Tepekule, A. E. Pusane, H. B. Yilmaz, C. B. Chae, and T. Tugcu, "ISI mitigation techniques in molecular communication," *IEEE Transactions on Molecular, Biological and Multi-Scale Communications*, vol. 1, no. 2, pp. 202–216, 2015.

[31] B. Tepekule, A. E. Pusane, H. B. Yilmaz, and T. Tugcu, "A novel modulation technique in diffusion based molecular communication and its performance analysis," in *IEEE Signal Processing and Communications Applications Conference (SIU)*. IEEE, 2014, pp. 1110–1113.

[32] B. Atakan, S. Galmes, and O. Akan, "Nanoscale communication with molecular arrays in nanonetworks," *IEEETransactions on NanoBioscience*, vol. 11, no. 2, pp. 149–160, June 2012.

[33] H. Arjmandi, A. Gohari, M.N. Kenari, and F. Bateni, "Diffusion-based nanonetworking: A new modulation technique and performance analysis," *IEEE Communications Letters*, vol. 17, no. 4, pp. 645–648, 2013.

[34] A. Noel, K. Cheung, and R. Schober, "Improving receiver performance of diffusive molecular communication with enzymes," *IEEE Transactions on NanoBioscience*, vol. 13, no. 1, pp. 31–43, March 2014.

[35] N. Farsad and A. Goldsmith, "A molecular communication system using acids, bases and hydrogen ions," in *2016 IEEE 17th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, 2016, pp. 1–6.

[36] N. Kamaly, B. Yameen, J. Wu, and O. C. Farokhzad, "Degradable controlled-release polymers and polymeric nanoparticles: Mechanisms of controlling drug release," *Chemical Reviews*, vol. 116, no. 4, pp. 2602–2663, 2016.

[37] A. Gohari, M. Mirmohseni, and M. Nasiri-Kenari, "Information theory of molecular communication: Directions and challenges," *IEEE Transactions on Molecular, Biological and Multi-Scale Communications*, vol. 2, no. 2, pp. 120–142, 2016.

[38] C. Rose and I. S. Mian, "Inscribed matter communication: Part I," *IEEE Transactions on Molecular, Biological and Multi-Scale Communications*, vol. 2, no. 2, pp. 209–227, 2016.

[39] N. Farsad, Y. Murin, A. Eckford, and A. Goldsmith, "Capacity limits of diffusion-based molecular timing channels," *IEEE Transactions on Information Theory*, submitted. https://arxiv.org/pdf/1602.07757.pdf

[40] B. H. Koo, C. Lee, H. B. Yilmaz, N. Farsad, A. Eckford, and C. B. Chae, "Molecular MIMO: From theory to prototype," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 3, pp. 600–614, March 2016.

[41] N. Farsad, D. Pan, and A. Goldsmith, "A novel experimental platform for in-vessel multi-chemical molecular communications," in *IEEE Global Communications Conference (GLOBECOM)*, 2017, pp. 1–6.

[42] N. A. Abbasi, D. Lafci, and O. B. Akan, "Controlled information transfer through an in vivo nervous system," *Scientific reports*, vol. 8, no. 1, p. 2298, 2018.