Nanoparticle communications: from chemical signals in nature to wireless sensor networks

Song Qiu,[1] Weisi Guo,[1,*] Mark Leeson,[1] Siyi Wang,[2] Nariman Farsad[3] and Andrew Eckford[3]

[1] *School of Engineering, University of Warwick, United Kingdom*
[2] *Institute for Telecommunications Research, University of South Australia, Australia*
[3] *Department of Electrical Engineering and Computer Science, York University, Canada*

The need to convey information has always existed in both the animal and human kingdoms. The article offers a review of the latest developments in transporting information using nanosized particles. It begins by examining chemical signalling in nature, and goes on to discuss recent advances in mimicking this in bio-inspired engineering. It then points out the important difference between signalling and general communication, and explains why the latter is a more challenging problem. The existing research on mimicking chemical signalling in nature is a precurser to research into general chemical communication. A review of the latest theoretical research in general chemical communications is presented, along with the practical developments of the world's first nanoparticle communications test-bed. In the parts of the article, the authors discuss the potential research challenges and identify three important areas for future development: robustness, miniaturization, and scalability.

1. Introduction

The 21st century is likely to see an unprecedented technological shift towards smarter lifestyles and health services. That is to say, people in various roles will be able to make more informed decisions about their actions, based on on-demand data availability. In order to provide this information, machines and sensors need to communicate data from areas of interest to a data distribution network or central controller. This will occur on different levels. At the microscopic scale, swarms of nanorobots can perform targeted drug delivery. At the macroscopic scale, sensors need to report observations in challenging industrial environments.[1] A particular challenge is that such devices are often located in environments hostile to the deployment of

* Corresponding author. E-mail: weisi.guo@warwick.ac.uk
[1] T. Nakano, A. Eckford and T. Haraguchi. *Molecular Communication*. Cambridge: University Press (2013).

Nanotechnology Perceptions **10** (2014) 29–41
Received 28 January 2014

conventional radio frequency (RF) communications. This means traditional methods of RF communications are not always feasible.

More generally, the need to convey information between two separated entities has always existed, in both the animal kingdom and in human society. There are many methods in which data can be encoded, transported and decoded. In human society, common ways of communicating include delivering physical packets (mail), speech (acoustic waves), modulating electromagnetic waves at various frequencies (radio waves in air, and optical waves in fibres), and visual observation of physical movements (hand, flag, or smoke signals). In the animal kingdom, chemicals can also be used to convey very simple messages. This chemical signalling can exist on a cellular level, and also in an external environment.

A good question is, why would we devote our time and resources to study chemical communication? There is, of course, scientific curiosity: to better understand how organisms signal to each other. Important questions can be asked, such as *will a breakdown of signalling cause collapse in a colony?* Aside from this, chemical signalling can also inspire engineers to design chemical-based communication systems. On a microscopic scale, microsurgery and drug delivery robots will likely need to communicate with each other (Figure 1), and this cannot be achieved with conventional electromagnetic waves. This is primarily due to the antenna size and transmission energy constraints of electromagnetic wave-based communication systems. Nanosized particles can be emitted at a relatively low energy expenditure level, and allowed to propagate to neighbouring robots. This article will discuss such challenges in greater detail later on. In this section, we will examine how organisms signal in nature using chemical molecules, and how this can be extended to form a general communications system.

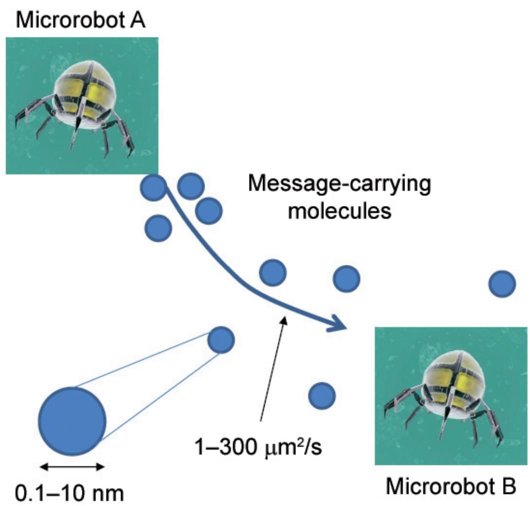

Figure 1. Illustration of nanoparticle communications between microsurgery robots.

A. Relationship to nanotechnology

On December 29, 1959, the later (1965) Nobel laureate in physics, Richard Phillips Feynman first envisioned the fabrication of devices at the atomic or molecular level in a speech entitled "*There's Plenty of Room at the Bottom*" delivered at an American Physical Society meeting at

Caltech. This was the first use of the concept of "nanotechnology". However, the actual term nanotechnology was first defined as "*a technology which mainly consists of the processing, separation, consolidation, and deformation of materials by one atom or by one molecule*" by Professor Norio Taniguchi of the Tokyo University of Science in 1974. Nanotechnology opens up an entirely new set of possibilities to the communications community for dealing with entities (particles) sized between 1 and 100 nanometres (Figure 1), known as nanoparticles. Molecular communications in the nanotechnology engineering sense, defined as the use of molecules as messengers between transmitters and receivers, is the most promising approach for nanonetworks[2] compared to realizations through nanomechanical, acoustic or electromagnetic means for communication between nanomachines to accomplish tasks ranging from computing and data storage to sensing and actuation.[1] This is due to the fact that mechanically direct contact between transmitters and receivers is needed in the transmission of information for nanomechanical communication and the underpinning principles of traditional acoustic transducers and electromagnetic transceivers also make transmission infeasible at the molecular scale.

B. Chemical signalling in nature

In terms of nanocommunications in nature, the idea of chemical molecules acting as information carriers is not new. There is a trail of evidence stretching back from ancient Greece, through the Renaissance, and to Charles Darwin's work on evolution.[3] However, the term "pheromone" is a 20th century Greek construction, meaning to transfer (*pherein*) excitement (*hormon*) between members of the *same species*. Over the past 50 years, research has identified the chemical signalling process in several species of moths, elephants and fish.[4] They are also used by algae, yeast and bacteria.

It is important to distinguish the two different hierarchies of communicating chemical-encoded messages between entities A and B:[4]

- *Cues* involve entity A detecting an event at entity B, and inferring some property about B, which B did not intentionally want to reveal. For example, a blood-sucking insect (entity A) finds its host (entity B) by using the concentration gradient of CO_2 molecules emitted by the host. The host does not emit CO_2 molecules for the purpose of signalling, so this is not a form of true communication. However, cues have the property that information can be inferred from chemical molecules.
- *Chemical signals* are pheromones that convey a specific message and serve no other purpose. Many organisms have evolved glands that create (encode) and secrete (transmit) the message into the environment, and glands that receive the signal and decode the message. This is called chemical signalling; there is a finite, very small number of possible messages; general communication of data is not achieved.

---

[2] J.M.J.I.F. Akyildiz and M. Pierobon. Nanonetworks: A new frontier in communications. *Communications of the ACM* **54** (2011) 84–89.
[3] T.D. Wyatt. Fifty years of pheromones. *Nature* **457** (2009) 262–263.
[4] T. Wyatt. *Pheromones and Animal Behaviour: Communication by Smell and Taste*. Cambridge: University Press (2003).

Whilst it is feasible that chemical signals can evolve into systems that can represent any generic message as a chemical pattern, there is very little evidence that this has occurred in nature.

C. General communication using chemical molecules

In order to achieve general communication, one needs to transduce any message into a unique chemical pattern, and to reliably transport messages as a continuous stream of chemicals.

The chemical pattern could vary in many ways. Hypothetically, variations can exist in several orthogonal domains, namely: concentration of different chemical compounds; the pattern of variation of concentration in time; and perhaps also any chemical reactions that the compounds can cause at the receiver. This is analogous to how electromagnetic waves are encoded in modern communication systems. Figure 2 shows the classical simplified steps of transforming a generic message (e.g., a photograph) into a physical signal. In the first instance, the message is encoded into a generic format, such as a binary code. The binary code is typically further augmented by two more subprocesses, namely: (i) line coding to improve the features of the binary code; and (ii) error correction coding to add redundancy to the code. After this the code is transduced into physical carriers. In the case of electromagnetic (EM) waves, there are three classical methods of transduction by modulation, each of which changes a physical property of the wave to represent the coded information. In the case of chemical molecules, we suggest two modulation methods, namely: (i) modifying the concentration of the chemical compound; and (ii) mixing different chemical compounds. We will discuss these in greater detail later in the article.

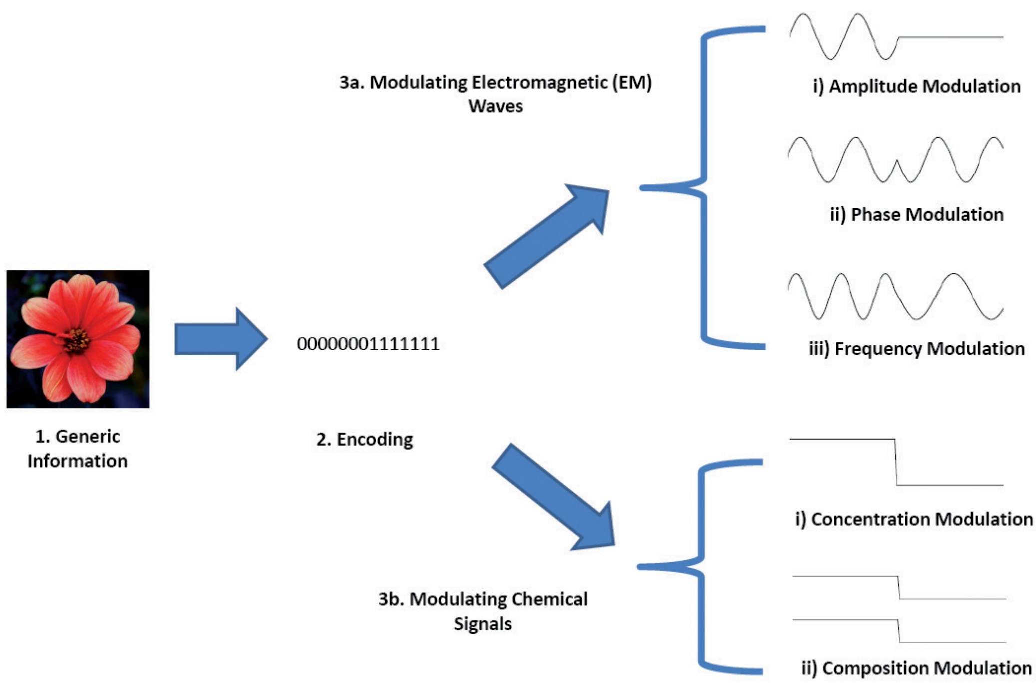

Figure 2. Illustration of transforming a general message (photo) into a binary code (encoding), and transmitting it using either EM waves or chemical compounds.

2. Replicating pheromone signalling

Over the past decade, there has been significant effort to replicate the chemical signalling process. International projects such as the European Union (EU)-funded "Intelligent Chemical Communications" (iCHEM) project used electronic components to replicate the pheromone production, emission and reception process.[5,6] Chemical signalling has been proposed to have potential as a communication channel for a diverse range of systems. On the microscopic scale, it has been proposed to be an effective solution for communication between micro- or nanoscale devices,[1,7] such as labs-on-a-chip and body area sensor networks.[8] On a large scale, the use of molecular signalling has been implemented in robotics for control and distress signalling[9] and for estimating the size of a swarm of robots (quorum sensing).[10]

Figure 3 shows a more detailed example of how robots can be made to replicate the action of moths.[6] A pair of robots communicate using pheromones that mimic those used by female moths to attract male partners. The pheromones are produced as a chemical mixture and emitted using a spray system. Utilizing an induced air current to accelerate the diffusion process, the receiver robot can detect the pheromone using a biosensor array. The chemical signal is decoded at the receiver robot, which uses a field programmable gate array (FPGA) implementation of the moth's neuromorphic system.[6]

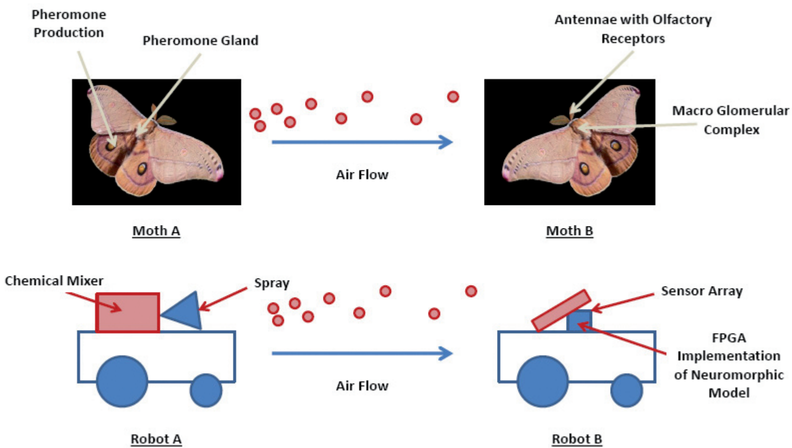

Figure 3. Illustration of robots replicating pheromone production, transmission and reception in moths.

[5] N. Dimov, L. Munoz, W. Bula, G. Carot-Sans, A. Geurrero and J. Gardeniers. A chemoemitter system mimicking chemical communication in insects. *Procedia Computer Science* **7** (2011) 142–143.

[6] M. Cole, Z. Racz, J. Gardner and T. Pearce. A novel biomimetic infochemical communication technology: from insects to robots. In: *Proc. 11th IEEE Sensors Conf.,* 28–31 October 2012, Taipei,Taiwan, pp. 1–4.

[7] T. Nakano, M. Moore, F. Wei, A. Vasilakos and J. Shuai. Molecular communication and networking: opportunities and challenges. *IEEE Transactions on NanoBioscience* **11** (2012) 135–148.

[8] O.B.A.B. Atakan and S. Balasubramaniam. Body area nanonetworks with molecular communications in nanomedicine. *IEEE Communications Magazine* **50** (2012) 28–34.

[9] A. Purnamadjaja and R. Russell. Pheromone communication in a robot swarm: necrophoric bee behaviour and its replication. *Robotica* **23** (2005) 731–742.

[10] A.H. Purnamadjaja and R.A. Russell. Bi-directional pheromone communication between robots. *Robotica* **28** (2010) 69–79.

3. Nanoparticle communications

A. Theoretical groundwork for nanocommunication

Despite all the recent work in chemical signalling, there have been few practical demonstrations of molecular communication systems that can be used to transfer generic messages in a continuous and reliable manner. One of the major obstacles to implementing molecular communication is the tedious, laborious and expensive nature of "wet lab" experimentation. Another challenge is the difficult nature of transducing generic signals into chemical compounds and emitting them in such a way that reliable reception can be achieved.

As a result, a large body of work on the theoretical aspects of microscopic molecular communication systems has been developed,[11–15] without any physical implementation of a fully functional communication device. The theoretical framework reveals interesting communication bounds for conveying data using nanoparticles. In this subsection, we will discuss the basis for a theoretical understanding of the communication limits and how they are applicable to real system implementation.

(1) Random walk—pulse response: Let us assume that the information-bearing nanoparticles undergo a random diffusion process (random walk). Let us consider an emitter that emits a single *pulse* of chemicals. We consider a single pulse because a generic communications system will modulate messages into a succession of individual pulses.

At time t after an emission, the probability density function of the molecule concentration at any point a distance x away from the point of emission follows an inverse Gaussian function:[16]

$$f(x,t) = \frac{1}{\sqrt{4D\pi t}} \exp\left(-\frac{x^2}{4Dt}\right), \tag{1}$$

for a given diffusivity D, which is a chemical medium-dependent measure of the rate of diffusion.

In order to *capture* the molecules at the receiver,[17] the probability of capture is:[15]

$$p_c(x,t) = \text{erfc}\left(-\frac{x}{2\sqrt{Dt}}\right). \tag{2}$$

For *intracellular* chemical signalling, the diffusivity D is 1–300 $\mu m^2/s$, and the diffusion distance x is 1–200 μm. In such a scenario, the probability of capturing 90% of more of the emitted molecules can be achieved in less than a millisecond.

[11] B. Atakan and O. Akan. An information theoretical approach for molecular communication. In: *IEEE Bionetics Conference*, pp. 33–40. December 2007, Budapest.
[12] M. Pierobon and I.F. Akyildiz. A physical end-to-end model for molecular communication in nanonetworks. *IEEE Journal on Selected Areas in Communications* **28** (2010) 602–611.
[13] M. Leeson and M. Higgins. Forward error correction for molecular communications. *Nano Communication Networks* **3** (2012) 161–167.
[14] K. Srinivas, A. Eckford and R. Adve. Molecular communication in fluid media: the additive inverse Gaussian noise channel. *IEEE Transactions on Information Theory* **8** (2012) 4678–4692.
[15] W. Guo, S. Wang, A. Eckford and J. Wu. Reliable communication envelopes of molecular diffusion channels. *Electronics Letters* **49** (2013) 1248–1249.
[16] B. Oksendal. *Stochastic Differential Equations: An Introduction with Applications*. Springer (2010).
[17] The molecules cannot be captured and then re-escape, participating infinitely in the process.

For *interorganism* chemical signalling, the diffusivity D is 0.1–1 cm/s^2, and the diffusion distance x is several metres. In such a scenario, the probability of capturing 90% of more of the emitted molecules can be achieved in a few minutes to an hour.

In reality, the diffusion process is assisted by currents both inside the body and between bodies. Air currents have the effect of rapidly accelerating the diffusion process and, hence, chemical communication over several metres becomes possible at speeds of the order of seconds to minutes.

(2) Pulse modulated signal: Given the pulse response in (1), a sequence of pulses can be examined. A key criterion for reliable detection of continuous pulses is to avoid overlapping pulses at the receiver, such that the response of one pulse overly interferes with the shape of another, which is known as intersymbol interference (ISI).

In EM-based signalling, digital filters are used to shape the transmitted pulses so that ISI is minimized. Fortunately for EM waves this is possible, as the time gap between pulses (milliseconds) is much greater than the characteristic time of the stochastic nature of the channel (nanoseconds). However, in chemical signalling the channel is extremely stochastic, and the delay spread of the channel can be of the order of seconds to minutes. This potentially means that, in order to avoid excessive ISI, the time separation between successive pulses needs to be of the order of seconds to minutes as well. In Figure 4 we illustrate pulse responses for EM-based multipath and chemical-based diffusion channels. As mentioned, the delay spread from multiple EM-waves reflecting off surfaces is small (10–50 nanoseconds over several kilometres in urban environments) compared to the guard time (T). This is primarily due to the speed of light and the absorbing nature of materials such that the energy from multiple reflexions is often lost. However, for molecular diffusion this is not the case. The delay spread can be several seconds over just a few metres of space.

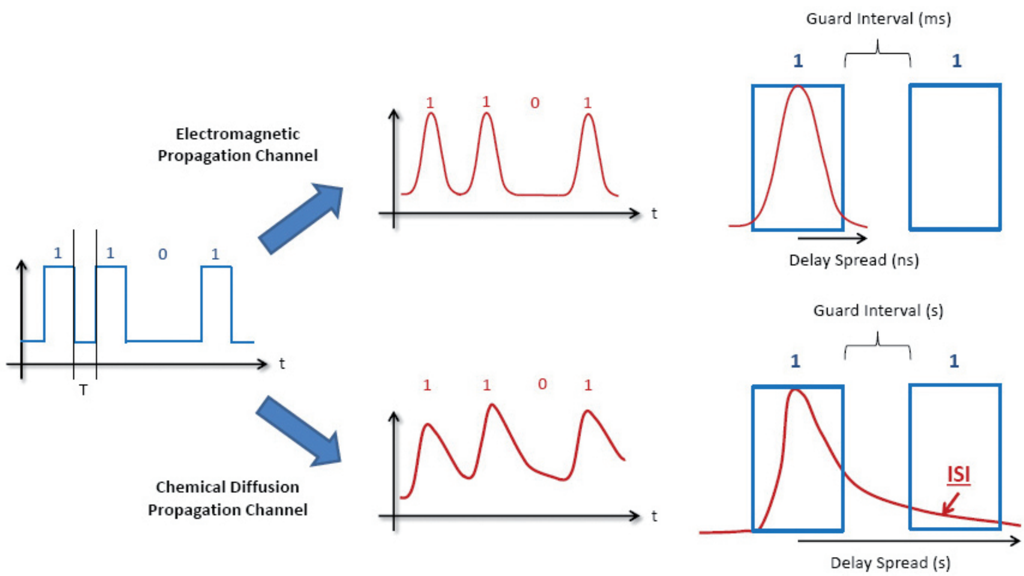

Figure 4. Illustration of pulse responses for EM-based multipath and chemical-based diffusion channels. The guard time (interval) for radio communications (milliseconds) is typically much greater than the delay spread (nanoseconds), whereas the guard interval for the molecular communication channel needs to be of the order of a second.

(3) Data rate scalability: The consequence of strong ISI in a chemical diffusion channel is that in order to achieve a reasonably reliable communication link, the channel capacity must be kept low (of the order of 0.1 bits/s per molecule type[15]). This may sound tremendously underwhelming when we consider that a modern wi-fi or 4G cellular link can provide up to 100 Mbits/s. However, we should be more careful when drawing such comparisons.

First of all, modern EM-based systems use bandwidth resource to scale up data rate R, which is given by the product of bandwidth B and capacity C, where the capacity is a function of the channel quality S:

$$R[\text{bits s}^{-1}] = B[\text{resource}] \times C(S)[\text{bits s}^{-1}\ \text{resource}^{-1}]. \tag{3}$$

The typically quoted $R = 100$ Mbits/s in modern communication systems is spread over a $B =$ 20 MHz channel, yielding a real channel capacity of $C = 5$ bits/s per unit frequency (Hz). This is achieved only when the signal power of the channel is $S = 1000$ (30 dB) times higher than the noise power. Furthermore, this is only realizable with state-of-the-art channel modulation and coding schemes, which have been developed over half a century.

In Table 1, we compare a modern EM-based 4G long term evolution (LTE) system, with our proprietary Kinboshi[18] molecular communications system. Now let us reconsider the channel capacity of a molecular channel, which is $C = 0.1$ bits/s per individual molecule type. If we can find a method of linearly scaling the chemical communication channel's capacity, we too can achieve a data rate R of the order of Mbits/s. To achieve this, one needs several million unique combinations of chemicals that mutually do not interfere with or contaminate each other. This is in principle possible with the large number of different odours and hydrocarbon combinations in existence and their detection can be made possible by cheap electronic noses,[19] or by more advanced methods still in development.

Table 1. Comparing electromagnetic (EM) with chemical communications.

Parameter	EM	Chemical
System	4G LTE	Kinboshi
Resource	Bandwidth (20 MHz)	Chemical types
Range	Very long (km)	Short (m)
Delay spread	Small (ns)	Long (s)
Reliability	Very high	Medium
Peak capacity	5 bits s^{-1} Hz^{-1}	0.1 bits s^{-1} $chemical^{-1}$
Emitter size limitation	$\propto$ Wavelength (mm–cm)	> Molecule size (nm)
Propagation law	Maxwell	Brownian motion
Artificial gain	Antenna gain	Drift currents
Emission type	Active (antenna)	Passive or active
Energy consumption	High ($\approx$ watts)	None (passive) or low (active)

[18] Kinboshi is the name given to the first nanoparticle testbed, developed by N.F. in conjunction with A.E. and W.G.

[19] L. Marques and A.T. De Almeida. Electronic nose-based odour source localization. In: *IEEE Proceedings of the 6th International Workshop on Advanced Motion Control* (2000), pp. 36–40.

B. Kinboshi: the first nanoparticle communications testbed

The idea of the nanoparticle communications testbed was conceived in summer 2012 by W.G., who invited A.E. to visit him and shared the idea. This spurred A.E.'s PhD student N.F. to develop the first nanoparticle testbed, which was completed in early 2013.[20]

In the article,[20] we describe the first modular and inexpensive means of performing nanoparticle communication experiments. Our system fills an important gap in the molecular communications literature, where much current work is done via simulation with simplified system models.

The demonstrator testbed is a first-generation device that the team (N.F., W.G. and A.E.) hopes will kick-start academic and industrial revolutions in designing molecular-based communication systems. The system is inexpensive to build and the platform is available for sale as a modifiable and reprogrammable research testbed. It consists primarily of a transmitter and a receiver, as illustrated in Figure 5. The propagation channel in between is several metres of either free-space or a specific structural environment (i.e., a tunnel network). On the transmission side, the hardware consists of: (i) a user interface for text entry; (ii) a microcontroller that converts the input text into binary sequences and then transduces the sequence into chemical signals; (iii) a reservoir of chemicals; and (iv) a chemical release mechanism. On the receiver side, the hardware consists of: (i) a chemical sensor; and (ii) a microcontroller that demodulates and decodes. The type of data we demonstrated was a short string of text data, because text-based information is of interest to sensor networks and command-based communication systems. For example, we are exploring the possibility of using molecular communications for structural health monitoring and giving commands to underground robots.

Figure 5. Photograph of world's first continuous molecular communication system.[20]

A key finding is the nonlinearity of our platform. This finding is very important because most current communication theory is based on linear systems. Although we were unable to find the exact reason for nonlinearity, we provide some guideposts. This motivates further investigation

[20] N. Farsad, W. Guo and A.W. Eckford. Tabletop molecular communication: text messages through chemical signals. *PLoS ONE* **8** (2013) e82935.

into the exact cause of the nonlinearity in future work. If it is shown that the nonlinearity is part of practical molecular communications systems (i.e., the nonlinearity cannot be resolved using better equipment), new communication-theoretic work may be necessary on this topic.

4. Applications of nanoparticle communications

A. Microscopic scale: nanomachines

Although nanomachines have not yet been widely devised or manufactured, molecular communications do appear to exist in nature. The potential applications of molecular communications can be categorized into several groups, including but not limited to biomedical, environmental, industrial and military applications and home appliances. The following is a summary of these applications adopted from the literature:[1]

- Since molecular communication is a biologically-inspired method, the most direct applications are in the biomedical field, where organs and tissues interact through the use of nanotechnologies, such as immune system support, biohybrid implants, drug delivery systems,[21] health monitoring[22] and genetic engineering;
- In an industrial context, nanocommunications can help with advances in new materials, manufacturing processes and quality control procedures, such as food and water quality control and functionalized materials and fabrics;
- Nanonetworks in military scenarios can vary widely depending on the application.[2, 8, 23] In large area deployment, the classic application can be nuclear, biological and chemical (NBC) defences. Nanonetworks can be deployed over the battlefield or targeted areas to detect aggressive chemical and biological agents and coordinate a defensive response. Another application, similar to the consumer goods field but focusing on military equipment, is nanofunctional equipment. Advanced materials containing nanonetworks can be used to manufacture equipment capable of self-regulating the temperature beneath soldiers' clothes and even detecting whether the soldier has been injured;
- Finally, nanonetworks can be applied to the environmental field due to their biological inspiration to achieve some goals that have not been solved with current technologies. These include the area of biodegradation processes, an existing and growing problem with garbage handling throughout the world, with which nanonetworks can help by sensing and tagging different materials, which can be later located and processed by smart nano-actuators; animals and bio-diversity control, where nanonetworks acts to control several species and their presence in particular areas; air pollution control (similar to the quality control applications), where air pollution levels can be monitored and harmful substances in the air can be removed by nanofilters to improve its quality.

---

[21] R. Singh and J.W. Lillard, Jr. Nanoparticle-based targeted drug delivery. *Experimental and Molecular Pathology* **86** (2009) 215–223.

[22] S.H.Y. Moritani and T. Suda. Molecular communication for health care applications. In: *Fourth Annual IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom)* (2006), pp. 1–5.

[23] D. Malak and O.B. Akan. Molecular communication nanonetworks inside the human body. *Nano Communication Networks* **3** (2012) 19–35.

More specifically, the technical motivation behind using molecules to carry information lies in challenging electromagnetic (EM) propagation environments. In many industrial applications, wireless sensors are distributed in embedded locations. Such locations restrict the level of human access, antenna size and the ease of EM wave propagation. For such sensor applications, there is often a requirement to design small sensors that can deliver data without a communication line and at very low energy levels. Other applications include creating lab-on-a-chip systems, which can both perform biochemical experiments and analyse the experimental data.

B. Macroscopic scale: structural health monitoring

Recently researchers at Warwick University have shown that the Kinboshi system can reliably transport data across confined structural environments, especially in cases where conventional EM-wave based systems may fail. Examples include monitoring corrosion in structures (e.g., bridge casings, pipe and tunnel networks), and also in areas where one wants to minimize electromagnetic radiation (e.g., hospitals), or which suffer from excess radiation interference (e.g., space).

The challenge in many industrial applications is that the metallic tanks are connected by complex pipes (e.g., ventilation pipes) and EM waves do not necessarily propagate well through complex pipe technologies. This is especially the case when the pipes cannot act as a waveguide for the data-bearing EM waves. This could be because there are constraints to what EM frequency bands are available for use and restrictions on the antenna dimensions required to generate the appropriate waves. Alternative solutions include drilling holes to create an improved EM propagation path between the containers, or deploying a wired communication system. Drilling holes through the tanks is not an attractive solution as the tanks might be filled with fluids or gases, or the holes might otherwise compromise the tank's function. A wired solution is not attractive as it requires prior infrastructure deployment in the pipe network and can cause blockages in the long run. Therefore, data needs to be communicated through the pipes without wires. Figure 6 illustrates the experimental setup between an observation zone and a data collection zone. Each zone consists of a metal tank, interconnected by an iron pipe network. The two tanks are defined as two zones: (i) *observation zone*, we assume there is an event of interest (e.g., state of the contents of a storage tank, structural integrity of the tank itself), and there are sensors to detect the event and report the data wirelessly; (ii) *data collection zone*, there are receivers that await the data reported from the observation zone. The pipe network is a flexible design, whereby the length of individual pipe sections and the number of bends can be adjusted.

Conducted research[24] demonstrated that EM-wave based communication links (Zigbee sensors) are unreliable in such confined environments (when a pipe network cannot act as a waveguide). However, the Kinboshi molecule-based communication system can slowly but reliably transport data. This is an encouraging sign demonstrating that in certain difficult environments the dominance of EM-wave systems can be challenged by our novel molecular communications system.

[24] S. Qiu, W. Guo, S. Wang, N. Farsad and A. Eckford. A molecular communication link for monitoring in confined environments. In: *IEEE Intl Conf. on Communications (ICC)*, 10–14 June 2014, Sydney, Australia, pp. 718–723.

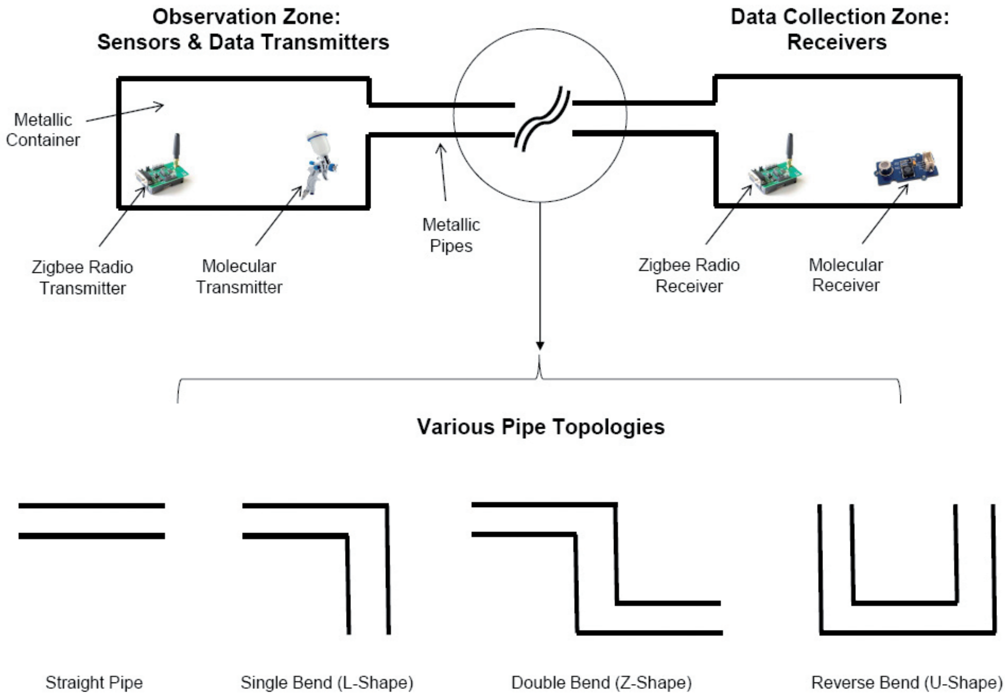

Figure 6. Illustration of propagation environment consisting of two metallic boxes connected by a metallic pipe with various lengths and bends.

5. Challenges and future research vectors

There are a number of challenges that we have not discussed in great detail. They mainly relate to the challenging stochastic nature of diffusion and its sensitivity to environmental conditions. Like all technologies in their infancy, there are significant scientific and engineering barriers to entry that one needs to overcome. However, this defines cutting-edge research and differentiates it from incremental progression. The primary areas of research the authors are examining are:

- *Robustness in uncertain and unknown environments:* being able to reliably communicate in complex and dynamic environments is an important desired advantage of molecular communications. Many factors such as ambient air currents, temperature variations and chemical contamination can strongly affect the diffusion of molecules. How to transmit pulses with partial, statistical or no knowledge of the environment is a challenging and important question;
- *Miniaturization to micro- and nanoscales:* being able to miniaturize the Kinboshi system to serve the purposes of communication between nano- and micromachines is critical to enabling nanonetworks. The challenge is to create the necessary electronics and electro-mechanical components to manufacture such a system;
- *Scalability to high data rate delivery:* being able to scale the data rate from ≈ 0.1 bits/s per chemical type to ≈ 1 Mbits/s across a million unique chemical compounds is challenging and critical to moving towards meaningful data delivery volumes.

There are other research challenges as well, which go towards making the aforementioned broad targets possible. The characterization of noise and different propagation channels for molecular communication is an important one, as is improving the design of the system itself. We leave this for future researchers to explain in detail.

6. Concluding remarks

The need to convey information has always existed in both the animal and human realms. There is now an increased focus on communicating in extreme environments, such as between microrobots performing targeted drug delivery, and between embedded sensors in industrial infrastructures. The article offers a review of the latest developments in transporting information using nanosized particles. The article first examined the usage of chemical signalling in nature, and went on to discuss the recent advances in mimicking this in bio-inspired engineering. An important distinguishing feature is the difference between signalling and general communication; the article explains why the latter is a more challenging and useful problem to solve.

This challenge has inspired a decade of theoretical work into finding the information rate (capacity) bounds for molecular communication. A great deal of speculation has been made with regards to the noise, propagation, and receiver properties of such a system. What has been missing is a working prototype, one that can be used to validate hypotheses and provide valuable experimental data. The article reviews the first working version of such a prototype, and goes on to discuss the three most salient challenges ahead, namely robustness, miniaturization and scalability.