Nano-Particle Communications: from Chemical Signals in Nature to Wireless Sensor Networks

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***Abstract*—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 nano-sized particles. The article begins by examining the usage of chemical signaling in nature, and go on to discuss the recent advances in mimicking this in bio-inspired engineering. The article then distinguishes the important difference between signalling and general communications, and explains why the latter is a more challenging problem.**

The article then goes on to examine existing research on mimicking chemical signaling in nature, which is a pre-curser to research in general chemical communications. A review of the latest theoretical research in general chemical communications is presented, along with the practical developments of the world's first nano-particle communications test-bed. In the end, the authors discuss the potential research challenges and name three important areas for future development: robustness, miniaturization, and scalability.

I. Introduction

The 21st century will 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 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 nano-robots can perform targeted drug delivery. At the macroscopic scale, sensors need to report observations in challenging industrial environments [1]. The challenge is that such devices are often located in environments that are hostile to the deployment of 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 fibers), 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. The chemical signalling can exist on a cellular level, and also in an external environment.

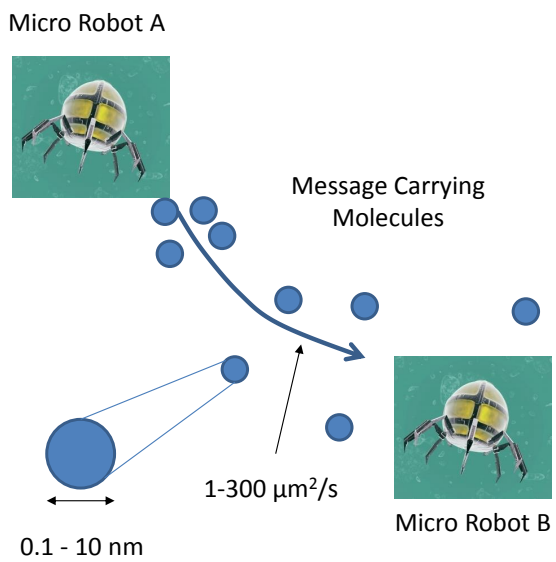

Fig. 1. Illustration of nano-particle communications between micro-surgery robots.

A good question is why would we devote our time and resources to study chemical communications? There is of course scientific curiosity, to better understand how organisms signal to each other. Important questions can be asked, such as: *will a break down of signalling cause collapses in colonies?* Aside from this, chemical signalling can also inspire engineers to design chemical based communication systems. On a microscopic scale, micro surgery and drug delivery robots will likely need to communicate with each other (Fig. 1), and this cannot be achieved with conventional electromagnetic waves. This is primarily due to the antenna size and transmit energy constraints of electromagnetic wave based communication systems. Nano-sized 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 using chemical molecules in nature, and how this can be extended to form a general communications system.

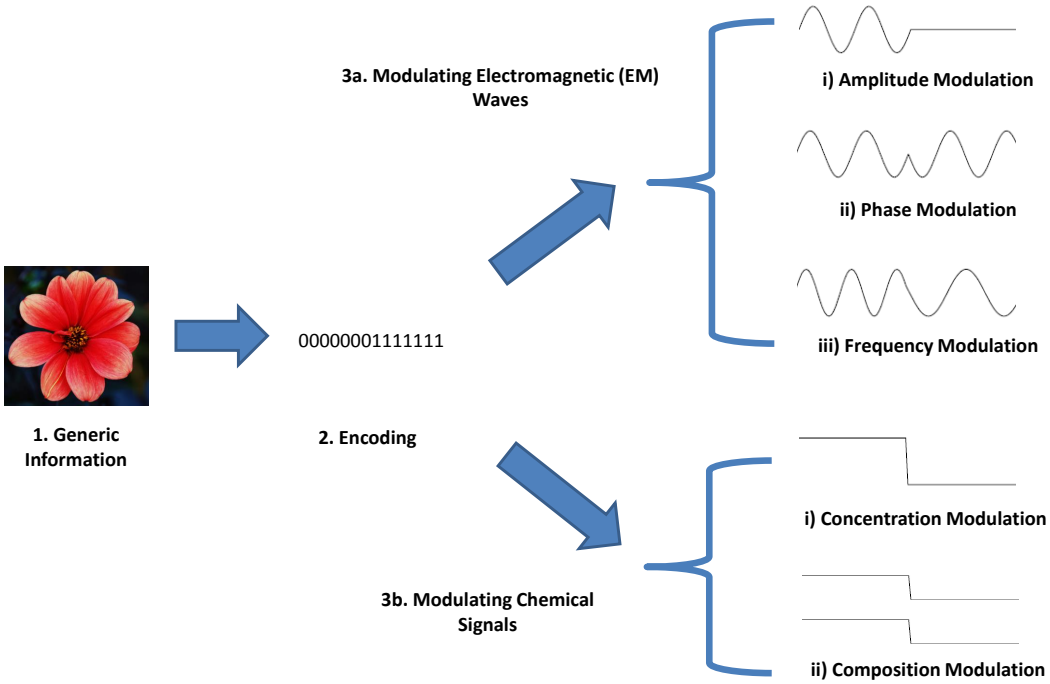

Fig. 2. Illustration of transforming a general message (photo), into a binary code (encoding), and transmitting it using either EM waves or chemical compounds.

A. Relationship to Nano-Technology

On December 29, 1959, the Nobel laureate in physics, Richard Phillips Feynman first envisioned the fabrication of devices at the atomic or molecular level in his speech entitled *"There's Plenty of Room at the Bottom"* delivered at an American Physical Society meeting at Caltech. This is the first use of the concept of 'nanotechnology'. However, the term *nanotechnology* was first defined as *"a technology which mainly consists of the processing of, separation, consolidation, and deformation of materials by one atom or by one molecule"* by the Professor Norio Taniguchi at Tokyo Science University in 1974. Nanotechnology opens up an entirely new set of possibilities to the communications community to deal with entities at particles sized between 1 and 100 nanometres (Fig. 1), known as nano-particles. Molecular communications in the nanotechnology engineering sense, defined as the use of molecules as messages between transmitters and receivers, is the most promising approach for nano-networks [2] compared to the realisations through nano-mechanical, acoustic, electromagnetic communication means between nano-machines 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 nano-mechanical communication and the underpinning principles of traditional acoustic transducers and electromagnetic transceivers also make the transmission infeasible at the molecular scale.

B. Chemical Signalling in Nature

In terms of nano-communications 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 pheromones is a 20th century term, meaning: to transfer (*pherein*) excitement (*hormon*) between members of the *same species*. Over the past 50 years, research has 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. We distinguish them below [4]:

- *Cues* involve entity A detecting an event at entity B, and inferring some property about B, that 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 doesn't emit CO_2 molecules for the purpose of signalling, so this is not a form of signalling or communications. However, cues have the property that information is 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, because there are very small finite number of messages, and general communication

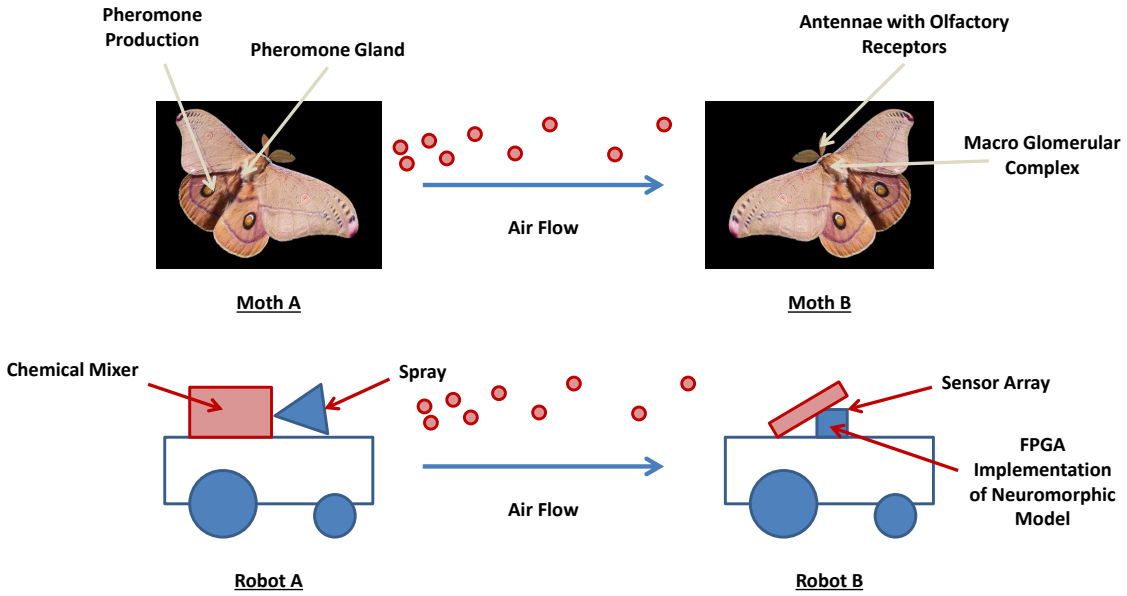

Fig. 3. Illustration of robots replicating the pheromone production, transmission, and reception in moths.

of data is not achieved.

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 Communications using Chemical Molecules

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

The chemical pattern can vary in many ways. Hypothetically, the variations can exist in several orthogonal domains, namely: the strength of different chemical compounds, the variation of compound strengths 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 general 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 sub-processes, namely: i) line coding improves the features of the binary code, and ii) error correction coding adds redundancy in the code. After which, the code is modulated onto physical carriers. In the case of electromagnetic (EM) waves, there are three classical modulation methods, 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.

II. Replicating Pheromone Signalling

Over the past decade, there has been significant efforts 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 on a diverse range of systems. On the microscopic scale, it has been proposed to be an effective solution for communication between micro- or nano-scaled devices [1], [7] such as lab-on-a-chip devices 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], 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 in a chemical mixture and emitted using a spray system. Utilizing an induced down-drift air current to accelerate the diffusion process, the receiver robot can detect the pheromone using a bio-sensor array. The chemical signal is decoded at the receiver robot, which uses a field-programmable gate array (FPGA) implementation of the

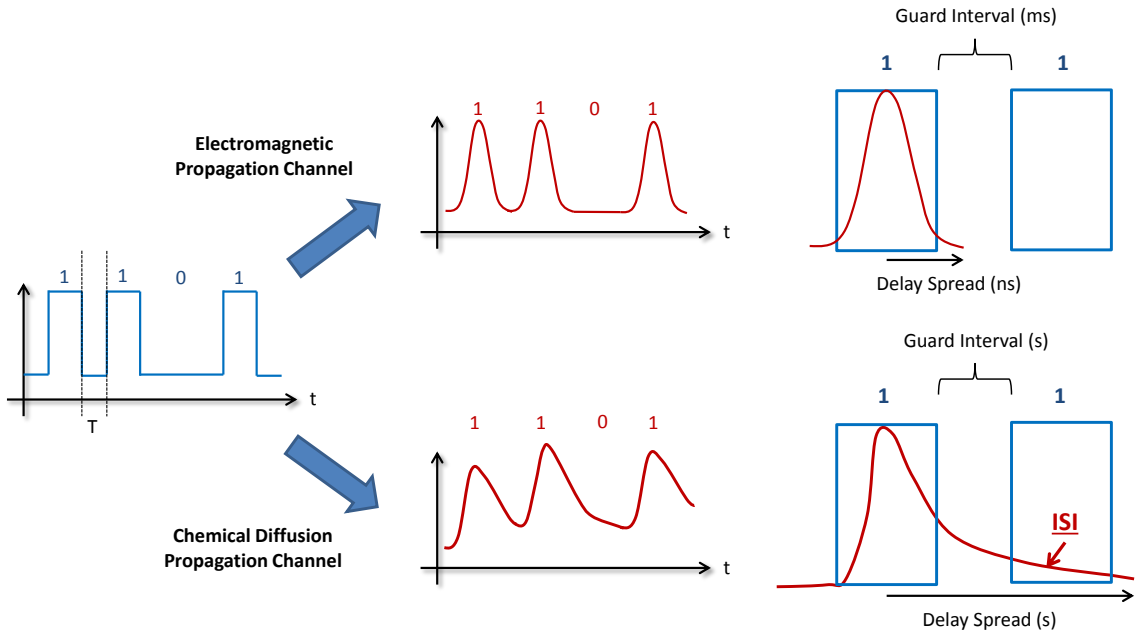

Fig. 4. Illustration of pulse responses for EM-based multi-path and chemical-based diffusion channels. The time guard interval for radio communications (milliseconds) is typically much greater than the delay spread (nanoseconds), whereas the guard interval for the molecular communication channel needs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

moth's neuromorphic system [6].

III. Nano-Particle Communications

A. Theoretical Groundwork for Nano Communications

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 in implementing molecular communication is the tedious, laborious and expensive nature of wet lab experimentation. Another challenge is the difficult nature of modulating generic signals onto chemical compounds, and emitting them in such a way that a 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 nano-particles. In this subsection, we will discuss the basis for a theoretical understanding of the communication limits, and how it is applicable to real system implementation.

1) Random Walk - Pulse Response: Let us assume that the information bearing nano-particles undergoes 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 x away from the point of emission follows an inverse exponential 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 [1], the probability of capture is [15]:

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

For *intra-cellular* chemical signalling, the diffusivity D value is 1–300 $\mu\text{m}/s^2$, 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 milli-second.

For *inter-organism* chemical signalling, the diffusivity D value 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 an effect of rapidly accelerating the diffusion process and hence, chemical communications over several metres is capable at speeds in the order of seconds to a minute.

2) Pulse Modulated Signal: Given the pulse response in (2), a sequence of pulses can be examined. A key criterion for reliable detection of continuous pulses is to avoid overlapping

[1] the molecules can not be captured and then re-escape, and participate infinitely in the process

TABLE I
COMPARING ELECTROMAGNETIC (EM) WITH CHEMICAL COMMUNICATIONS

Parameter	*EM*	*Chemical*
System	4G LTE	Kinboshi
Resource	Bandwidth (20MHz)	Chemical Types
Range	Very Long (km)	Short (m)
Delay Spread	Small (ns)	Long (s)
Reliability	Very High	Medium
Peak Capacity	5 bits/s/Hz	0.1 bits/s/chemical
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)

pulses at the receiver, such that the response of one pulse overly interferes with the shape of another. This is known as inter-symbol-interference (ISI).

In EM-based signaling, digital filters are used to shape the transmit pulses so that ISI is minimized. Fortunately for EM waves this is possible, as the time gap between pulses (milli-seconds) is much greater than the stochastic nature of the channel (nano-seconds). However, in chemical signaling the channel is extremely stochastic, and the delay spread of the channel can be in the order of seconds to minutes. This potentially means, in order to avoid excessive ISI, the time separation between successive pulses need to be in the order of seconds to minutes as well. As shown in Fig. 4, we illustrate pulse responses for EM-based multi-path and chemical-based diffusion channels. As mentioned, the delay spread from multiple EM-waves reflecting off surfaces is small (10–50 nano-seconds in urban environments over several kilometres) 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 reflections are 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. An analogy would be the scent or smell that lingers indefinitely.

3) Data Rate Scalability: The resulting consequence of strong ISI in the chemical diffusion channel is that in order to achieve a reasonably reliable communication link, the channel capacity is low (in 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 the bandwidth resource to scale up its data rate. The data rate R is given by the product of the bandwidth B and the capacity C, whereby the capacity is a function of the channel quality S:

$$R[\text{bits/s}] = B[\text{resource}] \times C(S)[\text{bits/s/resource}]. \quad (3)$$

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 (30dB) times higher than the noise power. Furthermore, this is only realizable with state of the art channel modulation and coding schemes, that have been developed over a period of 50 years.

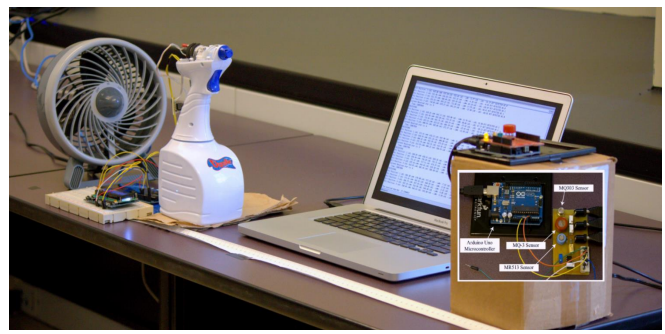

Fig. 5. Photograph of world's first continuous molecular communications system [18].

In Table I, we compare a modern EM-based 4G Long Term Evolution (LTE) system, with our proprietary Kinboshi [2] 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 data rate R in the order of Mbits/s. To achieve this, one needs several million unique combinations of chemicals that mutually do not interfere or contaminate each other. This is possible with the large number of different odors and hydrocarbon combinations in existence and their detection can be made possible by cheap electronic noses [17] or by more advanced methods that are in development.

[2]Kinboshi is the name given to the first nano-particle test-bed, developed by Dr. Nariman Farsad in conjunction with Dr. Eckford and Dr. Guo

B. Kinboshi First Nano-Particle Communications Test-bed

The idea of the nano-particle communications test-bed was conceived in summer 2012 by Dr. Weisi Guo, who invited Dr. Andrew Eckford to visit him and shared the idea. This spurred Dr. Eckford's PhD student Dr. Farsad to develop the first nano-particle test-bed, which was completed in early 2013. The seminal paper on its design and operation can be found in [18]. Since then, it has received reviews in a number of international press articles, most notably in the Royal Society for Chemistry, the Wall Street Journal, the Wired Magazine, Yahoo News, and CBS News.

In the article [18], we describe the first modular and inexpensive means of performing nano-particle communications experiments. The system fills an important gap in the molecular communication literature, where much current work is done in simulation with simplified system models.

The demonstrator test-bed is a first-generation device that the team (Dr. Farsad, Dr. Guo and Dr. Eckford) 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 re-programmable research test-bed. The test-bed primarily consists of a transmitter and a receiver, as illustrated in Fig. 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 inter-face for text entry, ii) a micro-controller that converts the input text into binary sequences and then modulates the sequence on 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, ii) a micro-controller that demodulates and decodes. The type of data we demonstrated is a short string of text data, because text-based information is of interest to sensor networks and command-based communication systems. For example, the team members are exploring the possibility of using molecular communications for structural health monitoring and giving commands to underground robots.

A key finding is the nonlinearity of our platform. This finding is very important because most of current communication theory is based on linear systems. Although we were unable to find the exact reason for nonlinearity, we provided some guide posts. This motivates further study on the exact cause of the nonlinearity in future works. If it is shown that the nonlinearity is part of practical molecular communication systems (i.e. the nonlinearity cannot be resolved using better equipment), new communication theoretic work may be necessary on this topic.

IV. Applications of Nano-Particle Communications

A. Microscopic Scale: Nanomachines

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

- Since molecular communication is a biologically-inspired method of communications, the most direct applications are in the biomedical field, where organs and tissues interact through the use of nanotechnologies, such as immune system support, bio-hybrid implants, drug delivery systems [19], health monitoring [20], and genetic engineering;
- In an industrial context, nano-communications can help with the advances in new materials, manufacturing processes and quality control procedures, such as, food and water quality control and fictionalised materials and fabrics;
- Nano-networks in military scenarios can be widely variable depending on the applications [2], [8], [21]. In large area deployment, the classic application can be nuclear, biological and chemical (NBC) defenses. Nano-networks can be deployed over the battlefield or targeted areas to detect aggressive chemical and biological agents and coordinate the defensive response. Another application similar to the consumer goods field but focusing on military equipment is nano-functional equipment. Advanced materials containing nano-networks can be used to manufacture equipment which is capable of self-regulating the temperature underneath soldiers' clothes and even detecting whether the soldier has been injured;
- Finally, nano-networks can be applied in environmental fields due to their biological inspiration to achieve some goals which have not be solved with current technologies. These will include the area of biodegradation processes, an existing and growing problem with garbage handling throughout the world, which nano-networks can help with by sensing and tagging different materials that can be later located and processed by smart nano-actuators; animals and bio-diversity control, where nano-networks acts to control several species and their presence in particular areas; air pollution control, which is similar to the quality control application, where air pollution level can be monitored and the harmful substances contained in it can be removed by nano-filter to improve the air quality.

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 sized sensors that can deliver data without tether and at very low energy levels. Other applications include creating lab-on-chip systems, that can perform bio-chemical experiments and analyze the experimental data together.

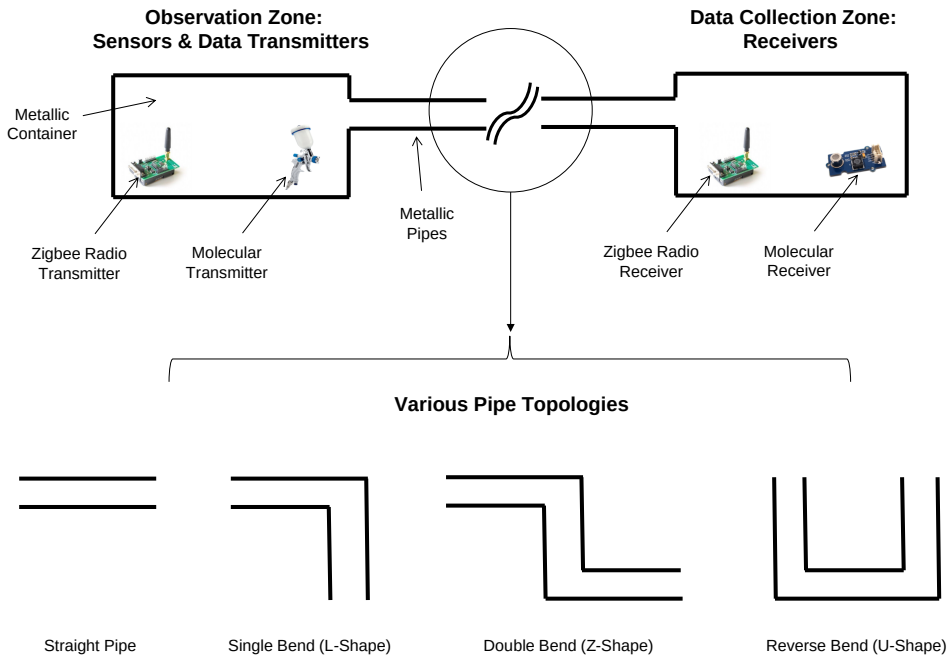

Fig. 6. Illustration of propagation environment consisting of 2 metallic boxes connected by a metallic pipe with various lengths and bends.

B. Macroscopic Scale: Structural Health Monitoring

In recent research, the 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. Example environments include monitoring corrosion in structures (e.g., bridge casings, pipe and tunnel networks), and also in areas where one wants to minimise electromagnetic radiation (e.g., hospitals) or 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 wave-guide to 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 can be filled with fluid or gas contents, or the holes can 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 forming 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 contents in 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.

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

V. Challenges and Future Research Vectors

There are a number of challenges which we have not discussed in great detail. These mainly relate to the challenging stochastic nature of diffusion and its sensitivity to environmental conditions. Like all technologies in its 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 process of molecules. How to transmit pulses with partial, statistical, or no knowledge of the environment is a challenging and important topic;

- *Miniaturization to Micro- and Nano-scale*: being able to miniaturize the Kinboshi system to serve the purposes of communications between nano- and micro-machines is critical to enabling nano-networks. 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, that go towards making the aforementioned broad targets possible. The characterization of noise and different propagation channels for molecular communications is an important one, as is improving the design of the system itself. We leave this for future researchers to explain in detail.

VI. Concluding Remarks

The need to convey information has always existed in both the animal and human kingdoms. There is now an increased focus to communicate in extreme environments, such as between micro-robots performing targeted drug delivery, and between embedded sensors in industrial infrastructures. The article offers a review of the latest developments in transporting information using nano-sized particles. The article first examined the usage of chemical signaling in nature, and go on to discuss the recent advances in mimicking this in bio-inspired engineering. An important distinguishment is the difference between signalling and general communications, and the article explains why the latter is a more challenging and useful problem to solve.

This challenge has inspired a decade of theoretical work on finding what the information rate (capacity) bounds are for molecular communications. A great deal of speculation is 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 hypothesis and provide valuable experimental data. The article reviews the first working version of such a prototype, and go on to discuss the three most salient challenges ahead, namely: robustness, miniaturization, and scalability.

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