

**Original citation:**

Guo, Weisi, Li, Bin, Wang, Siyi and Liu, Wei. Molecular communications with longitudinal carrier waves : baseband to passband modulation. IEEE Communications Letters .

**Permanent WRAP url:**

<http://wrap.warwick.ac.uk/68398>

**Copyright and reuse:**

The Warwick Research Archive Portal (WRAP) makes this work by researchers of the University of Warwick available open access under the following conditions. Copyright © and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable the material made available in WRAP has been checked for eligibility before being made available.

Copies of full items can be used for personal research or study, educational, or not-for profit purposes without prior permission or charge. Provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.

**Publisher's statement:**

“© 2015 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting /republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.”

**A note on versions:**

The version presented here may differ from the published version or, version of record, if you wish to cite this item you are advised to consult the publisher's version. Please see the 'permanent WRAP url' above for details on accessing the published version and note that access may require a subscription.

For more information, please contact the WRAP Team at: [publications@warwick.ac.uk](mailto:publications@warwick.ac.uk)



<http://wrap.warwick.ac.uk>

# Molecular Communications with Longitudinal Carrier Waves: Baseband to Passband Modulation

Weisi Guo<sup>1</sup>, Bin Li<sup>2</sup>, Siyi Wang<sup>3</sup>, Wei Liu<sup>4</sup>,

**Abstract**—Traditional molecular communications via diffusion (MCvD) systems have used baseband pulse modulation techniques by varying properties of molecular pulses such as the amplitude, the frequency of the transversal wave of the pulse, and the time delay between subsequent pulses. Given the difficulty of implementing chemical bandwidth, molecular communications has a limited data rate. In this letter, we propose and implement passband modulation by precisely controlling the longitudinal wave properties of molecules, effectively creating distinguishable carrier waves. This is achieved through a simple oscillation of the transmitter. Molecular frequency division multiplexing is achieved and we demonstrate that different molecular information streams can co-exist in the same space and time channel, creating bandwidth for MCvD.

## I. INTRODUCTION

Molecular communication via diffusion (MCvD) has attracted significant research interest in recent years [1]. MCvD exists in nature at both the nano-scale and macro-scale [2], offers certain energy and propagation advantages over wave-based communications [3], [4]. In terms of application, two interesting areas exist. In the field of nano-medicine, nano-robots will aim to track and operate on specific targets such as a tumor cell through sensing specific chemicals released by the cancerous region.

Fundamentally, MCvD involves modulating digital information onto the property of a single or a group of molecules. Regarding the diffusion channel, consider a 3-dimensional molecular diffusion channel with a transmitter and a receiver separated by distance  $d$ , with a molecular diffusivity  $D$ . The diffusion channel transfer function as a function of time  $t$  is:

$$h(t) = \frac{1}{(4\pi Dt)^{\frac{3}{2}}} \exp\left[-\frac{d^2}{4Dt}\right]. \quad (1)$$

Alternative channel transfer functions exist that considers a receiver that captures molecules. The rate of molecules captured for a finite receiver of radius  $R$ , is [5]:  $h_c(t) = (d - R)/2\sqrt{\pi Dt^3} \exp[-(d - R)^2/4Dt]$ , which has a similar shape to  $h(t)$  in Eq.(1).

### A. Review: Molecular Baseband Modulation

For a fixed transmission distance of  $d$ , one can observe that there are essentially two main properties to modulate: the number of transmitter molecules  $M$ ; and the pulse delay

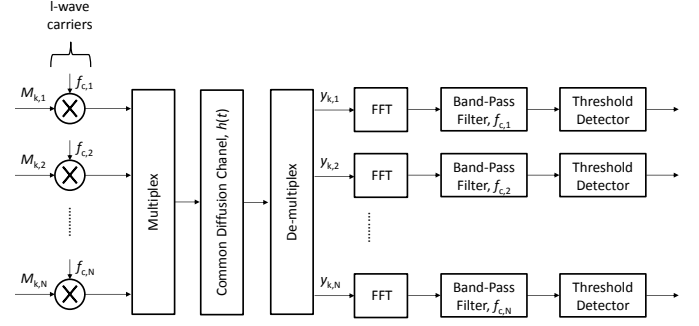


Fig. 1. Illustration of the modulation, multiplexing, de-multiplexing and demodulation process.

time  $T_k$ . For an input of binary symbols  $a_k \in \mathcal{A} = \{0, 1\}$ ,  $k = 0, 1, \dots, \infty$ , the output of the baseband pulse modulator is  $M_k$  (as shown in Fig. 1). Existing pulse modulation can be summarized as being one of the following:

- Amplitude / Concentration Shift Keying (ASK or CSK), where the information is modulated into different levels of  $M_k$ , i.e., Binary ASK:  $M_k \in \mathcal{M} = \{0, M\}$ .
- Frequency shift keying (FSK), where a sinusoidal pulse of a variable frequency  $f$  is emitted  $M_k(f_k) = M \sin(2\pi f_k t)$ , i.e., Binary FSK:  $f_k \in \mathcal{F} = \{0, f\}$ .
- Pulse Position Modulation (PPM), where the information is modulated into the bit delay time  $T$ , i.e., Binary PPM:  $T_k \in \mathcal{T} = \{0, T\}$ .

An example of a baseband transmitted signal and the received signals for both BASK and BFSK is presented in Fig. 2. In addition, the chemical composition can be used to encode information, as it is common in nature, which is known as Molecule Shift Keying (MoSK) [6]. However, the complexity of synthesizing and detecting even a small number of chemical compositions is complex and expensive.

### B. Contribution: Molecular Passband Modulation

The aforementioned modulations can be regarded as *baseband modulation*, whereby the performance is fundamentally limited by the inter-symbol-interference (ISI) due to the stochastic characteristic of diffusion. Whilst significant efforts have been made towards reducing ISI [7], baseband MCvD communication can only achieve a limited data rate, typically less than 1 bit/s per chemical type [8], [9], due to the lack of bandwidth. The concept of a carrier wave, such as that associated with electromagnetic wave communications, is absent in MCvD. This is due to the fact that until now,

<sup>1</sup> School of Engineering, University of Warwick, UK. <sup>2</sup> School of Information and Communication Engineering, Beijing University of Posts and Telecommunications, China. <sup>3</sup> Department of Electrical and Electronic Engineering, Xi'an Jiaotong - Liverpool University, China. <sup>4</sup> Department of Electronic and Electrical Engineering, University of Sheffield, UK

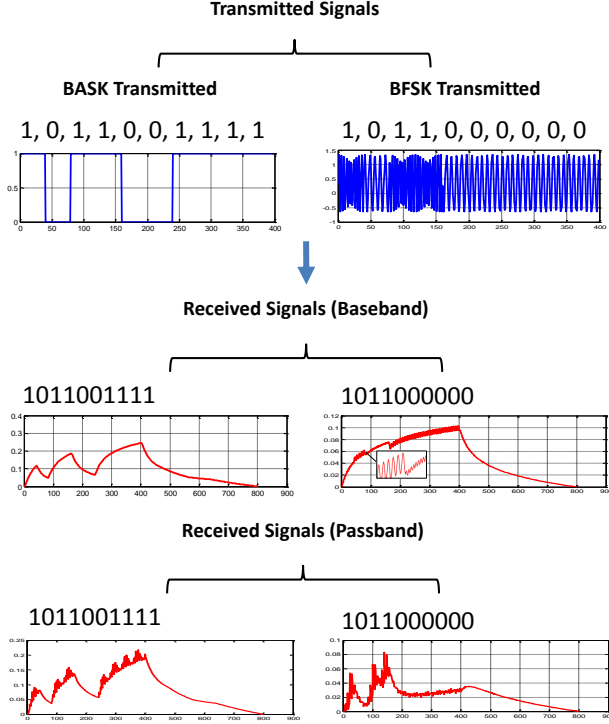


Fig. 2. Illustration of two different MCvD modulation techniques and the resulting baseband and passband received signals.

MCvD systems lack a continuous wave concept in what is fundamentally a discrete Gaussian kernel diffusion model.

The objective of this paper is to design a passband modulation system (see Fig. 1) for the transmission of  $N$  independent parallel molecular signals using a common chemical carrier via a common diffusion channel.

## II. CARRIER SIGNAL: LONGITUDINAL-WAVES

Electromagnetic (EM) wave carrier signals are *transverse waves*, where the oscillations occur perpendicular to the direction wave travels. In molecular communications, the arrival of particles at the receiver can be perceived as having a *longitudinal wave* (l-wave) property. If the frequency of the l-wave ( $f_{c,n}$ ) can be accurately controlled, it can be exploited as a carrier wave. Hence, there is *potential* for a limitless number of orthogonal molecular communication channels. As shown in Fig. 1, at the transmitter side: each baseband signal  $M_{k,n}$  will be modified by a carrier frequency of  $f_{c,n}$ . This will then pass through a common channel  $h(t)$  and be received by a common receiver that perform de-multiplexing through a combination of Fast Fourier Transforms (FFTs), band-pass filtering and threshold detection. The rest of the paper will explain each of the aforementioned elements in detail.

### A. Oscillating Transmitter

Consider a transmitter and a receiver that is separated by a distance  $d_0$  and the transmitter is allowed to oscillate along the transmission axis such that the instantaneous transmission distance varies according to:

$$d(t) = d_0 + A_c \sin(2\pi f_{c,k} t), \quad (2)$$

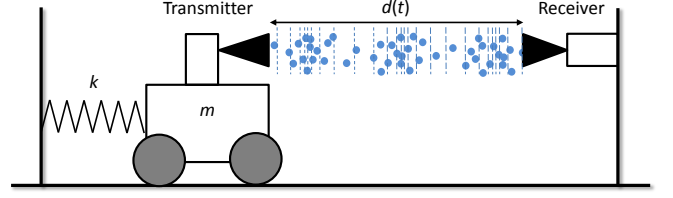


Fig. 3. Illustration of a potential l-wave carrier signal generation method using an oscillating transmitter.

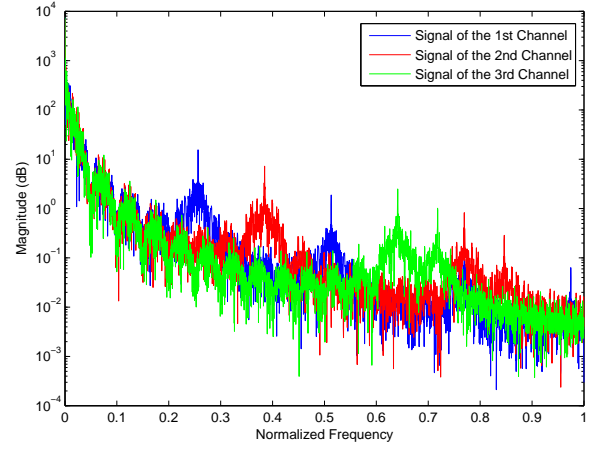


Fig. 4. Frequency response of  $N = 3$  molecular signals multiplexed over a single diffusion channel.

where  $A_c$  is the peak amplitude of oscillation. The parameter  $f_{c,k}$  is the frequency of the oscillation, and as we will show, it is also the frequency of the l-wave carrier signal. It is worth noting that as the random walk motion is a Martingale memoryless motion process, small disturbances caused by the oscillation of the transmitter doesn't greatly affect the general random motion process.

Therefore, for an input baseband modulation with amplitude  $M_{k,n}$ , the channel impulse response  $y_{k,n}(t)$  at any given point in time is derived from Eq.(1) to be:

$$y_{k,n}(t) = \frac{M_{k,n}}{(4\pi Dt)^{\frac{3}{2}}} \exp \left[ -\frac{(d_0 + A_c \sin(2\pi f_{c,k} t))^2}{4Dt} \right]. \quad (3)$$

In Fig. 2, at the top, we show the transmitted baseband signals for BASK and BFSK. In Fig. 2, at the bottom, we show the received baseband and passband signals. For passband modulation, it can be seen that an oscillatory component has been added, as well as non-linear effects due to the exponential term in the diffusion channel model given in Eq.(1).

### B. Multiplexing

In terms of implementing the multiplexer component, one way of doing so is by attaching a spring of stiffness  $K$  (N/m) to each transmitter (mass  $m$ ), such that the oscillation (l-wave carrier) frequency is given by:  $f_c = \frac{1}{2\pi} \sqrt{\frac{K}{m}}$ . This is illustrated in Fig. 3 for a well understood example of creating l-waves,

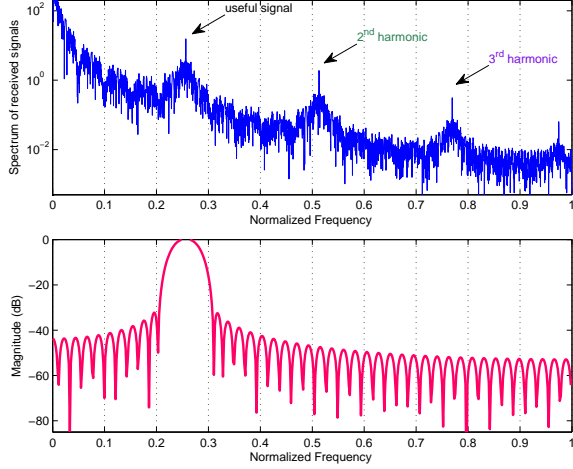


Fig. 5. (top) Frequency response of  $n = 1$  molecular signal with its harmonic peaks; (bottom) FIR magnitude of the bandpass filter designed to filter the first harmonic (useful signal).

where the spring stiffness can be adjusted to create different carrier frequencies. Alternative implementations are less mechanical, and can involve digitally controlled compression wave generators at the transmitter. In terms of parameters for the results, they are as follows: distance  $d_0 = 2\text{m}$ , diffusivity  $D = 0.1\text{cm}^2/\text{s}$ , the symbol period is  $4\text{s}$ , and the amplitude of oscillation is  $A_c = 0.2\text{m}$ . The discrete time index creates 10 samples for every second. The carrier frequencies for the  $N = 3$  links are:  $f_{c,1} = 5\text{Hz}$ ,  $f_{c,2} = 7.5\text{Hz}$ , and  $f_{c,3} = 12.5\text{Hz}$ . In terms of modeling using particle tracing, we recommend this to be carried in the future using commercial software such as COMSOL or open source particle simulators such as those found in [10].

### C. Frequency Response and De-multiplexing

We now consider  $N = 3$  independent data channels multiplexed together, each with the same baseband BASK modulation. At the common receiver, after FFT, the frequency response can be seen in Fig. 4. It can be seen that the baseband signal is at 0 normalized frequency. The first harmonic of each signal can be seen distinctively. To view the frequency response more clearly, we extract one of the 3 signals ( $n = 1$ ) and show its harmonic peaks in Fig. 5(top). In order to filter the first signal peak in Fig. 5(top), we use a finite impulse response (FIR) bandpass filter. Specifically, we use a Kaiser filter (parameter 3.3953) with a centre frequency of  $f_{c,n}$  for each  $n$  signal and a transition bandwidth of 0.05 or 0.10 normalized frequency. Due to the narrow nature of the bandpass filter, the FIR filter order is 92. Fig. 5(bottom) shows the magnitude of the frequency response.

Fig. 6(top) shows the post-filtering results in the time domain for one of the  $N = 3$  multiplexed signals. The results show that the original modulated signal can be fully reconstructed. A narrow passband (transition bandwidth = 0.05) is employed, which causes increased noise with increasing time due to frequency domain interference. This is due to

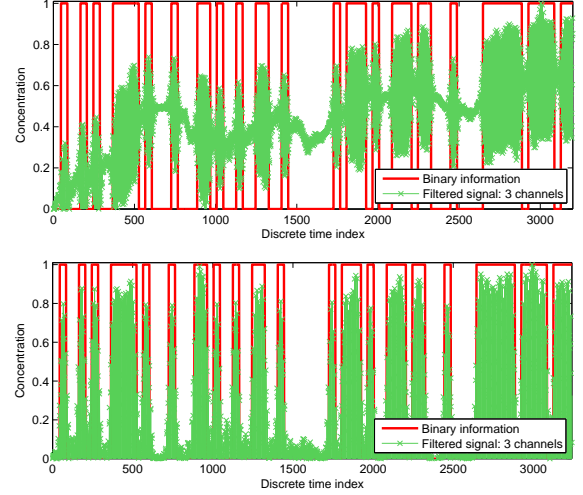


Fig. 6. Post-filtering results for a order 92 Kaiser bandpass filter with a transition bandwidth = 0.05 (normalized): (top) the filtered signal, (bottom) the filtered signal after the 1st order differential filtering.

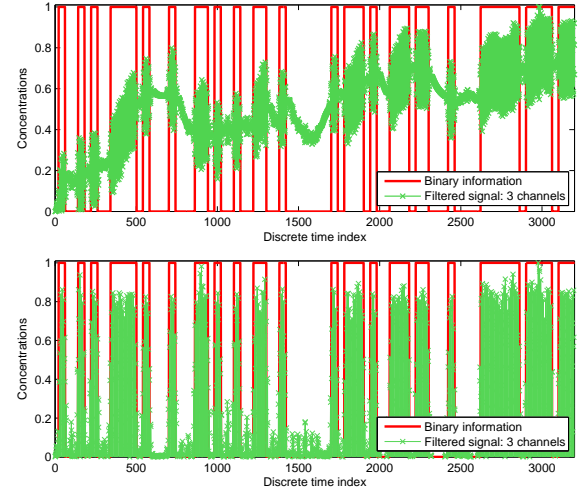


Fig. 7. Post-filtering results for a order 42 Kaiser bandpass filter with a transition bandwidth = 0.1 (normalized): (top) the filtered signal, (bottom) the filtered signal after the 1st order differential filtering.

the  $N = 3$  number of chemical information streams causing chemical interference (additive combining of molecules). As shown in Fig. 6(bottom), this can be further improved with a 1st order differential filter, as shown in the bottom sub-figure.

### D. Filter Complexity and Bandwidth

Some promising applications of molecular communications is likely to be with devices that operate with very low complexity and energy levels. In order to build energy efficient transmitter and receiver circuits, one particular challenge faced at the receiver side is the need for low-order bandpass filters, particularly those that can deal with the non-linear effects of the channel. We now examine the effect of reducing the previously employed FIR Kaiser bandpass filter order from 92 to 42. This complexity can be further reduced to 42.

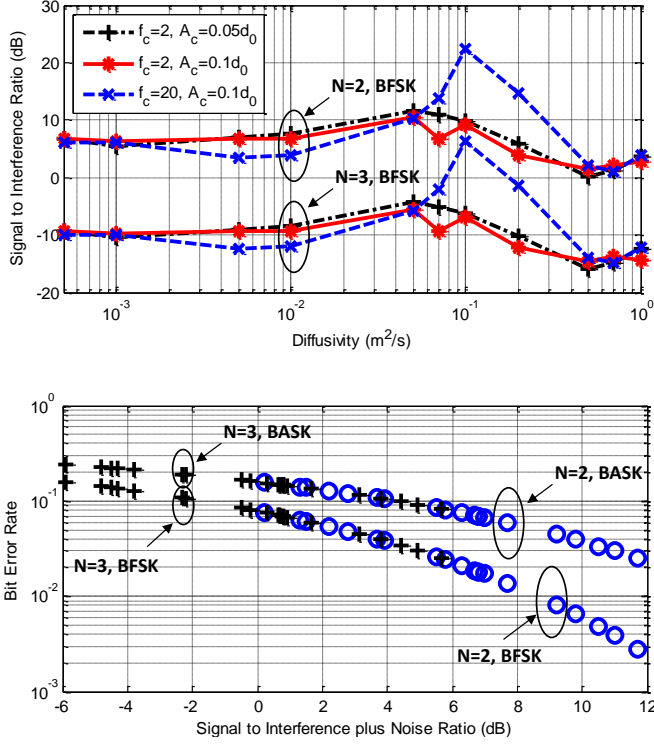


Fig. 8. Sensitivity analysis for  $N$  carriers with  $d = 2m$ : (top) SIR as a function of diffusivity  $D$ , for different carrier frequency  $f_c$  and vibration amplitude values  $A_c$ ; and (bottom) BER as a function of SINR, for BASK and BFSK baseband modulation schemes.

The result is that in order to achieve the same performance, the transition band has to be increased from 0.05 to 0.10. Fig. 7(top) shows the post-filtering results, which exhibits a similar increased noise with increasing time due to chemical interference. Therefore, in order to reduce the bandpass filter complexity, we need to increase the bandwidth and hence limit the number of carriers in co-existence. As before, as shown in Fig. 7(bottom), the performance can be further improved with a 1st order differential filter, as shown in the bottom sub-figure. The differential filter allows the system to employ more carrier channels, whilst reducing the noise in the demultiplexing process.

### III. SENSITIVITY ANALYSIS

The main goal of this letters is to create a sufficiently large number of parallel channels to improve system throughput and multiple access. Referring to Fig. 4 and Fig. 5 (top), one can see that the sidebands (harmonics) of a signal channel can potentially interfere with other adjacent frequency channels. Therefore, the multiple access performance will be dominated by the Signal-to-Interference Ratio (SIR), defined as the ratio between the signal power and the aggregate power of the adjacent harmonics. Whilst both scenarios can be avoided by placing the carrier frequencies ( $f_{c,1}, f_{c,2} \dots f_{c,N}$ ) sufficiently far apart, this would significantly reduce the spectrum utilization efficiency. Therefore, we are motivated to analyse the 2 interference cases: (1) 1 sideband (2nd harmonic) from adjacent channel interferes with the main signal channel ( $N = 2$ ),

and (2) 2 sidebands (2nd and 3rd harmonics) from adjacent channels interfere ( $N = 3$ , worst case scenario).

In Fig. 8 (top), the SIR is plotted as a function of diffusivity  $D$  for the  $N = 2$  and  $N = 3$  channel scenarios employing BFSK. The results show that the SIR varies by up to 10dB with different diffusivity  $D$  and carrier frequency  $f_c$  values, but it is not sensitive to the amplitude of vibration  $A_c$ . We suspect that there is an optimal carrier frequency for a particular set of channel parameters and leave this investigation for future work. In Fig. 8 (bottom), fixed power AWGN of 10dBm is added to the system (molecular channel noise can be modelled as AWGN [11]). The bit error rate (BER) is plotted as a function of the Signal-to-Interference plus Noise Ratio (SINR) for BASK and BFSK schemes. The results show that a reasonable BER ( $3 \times 10^{-3}$ ) can be achieved when only 1 sideband acts as interference ( $N = 2$ ), but not for the worst case scenario when 2 sidebands are considered ( $N = 3$ ), where the BER can exceed  $1 \times 10^{-1}$ .

### IV. CONCLUSIONS

In this paper we have presented a viable way of scaling the data rate of molecular communications by combining baseband modulation techniques with a longitudinal carrier wave generated by an oscillating transmitter. Our results have shown that  $N$  independent data streams using a common baseband modulation technique can be multiplexed together using different frequency longitudinal carrier waves and then reliably de-multiplexed using bandpass or highpass filters. A sensitivity analysis is also performed showing the worst-case SIR and BER performances.

### REFERENCES

- [1] T. Nakano, A. Eckford, and T. Haraguchi, *Molecular Communication*. Cambridge University Press, 2013.
- [2] T. D. Wyatt, "Fifty years of pheromones," *Nature*, vol. 457, no. 7227, pp. 262–263, Jan. 2009.
- [3] I. Llatser, A. Cabellos-Aparicio, and M. Pierobon, "Detection techniques for diffusion-based molecular communication," *IEEE Journal on Selected Areas in Communications (JSAC)*, vol. 31, pp. 726–734, 2013.
- [4] W. Guo, C. Mias, N. Farsad, and J. Wu, "Molecular versus Electromagnetic Wave Propagation Loss in Macro-Scale Environments," *IEEE Transactions on Molecular Biological and Multiscale Communications (T-MBMC)*, vol. 1, May 2015.
- [5] B. Yilmaz, A. Heren, T. Tugcu, and C. Chae, "Three-Dimensional Channel Characteristics for Molecular Communications With an Absorbing Receiver," vol. 18, 2014.
- [6] N. R. Kim and C. B. Chae, "Novel modulation techniques using isomers as messenger molecules for nano communication networks via diffusion," *IEEE Journal on Selected Areas in Communications (JSAC)*, vol. 31, Dec. 2013.
- [7] P. Shih, C. H. Lee, and P. Yeh, "Channel codes for mitigating intersymbol interference in diffusion-based molecular communications," in *IEEE Global Communications Conference*, Dec. 2012, pp. 4228–4232.
- [8] N. Farsad, W. Guo, and A. Eckford, "Tabletop molecular communication: Text messages through chemical signals," *PLOS ONE*, vol. 8, Dec. 2013.
- [9] K. Srinivas, A. Eckford, and R. Adve, "Molecular Communication in Fluid Media: The Additive Inverse Gaussian Noise Channel," *IEEE Trans. on Information Theory*, vol. 8, no. 7, pp. 4678–4692, Jul. 2012.
- [10] N. Farsad, A. Eckford, S. Hiyama, and Y. Moritani, "On-chip molecular communication: Analysis and design," *IEEE Transactions on NanoBio-science*, vol. 11, no. 3, pp. 304–314, Feb. 2012.
- [11] N. Farsad, N. Kim, A. Eckford, and C. B. Chae, "Channel and Noise Models for Nonlinear Molecular Communication Systems," *IEEE Journal on Selected Areas in Communications (JSAC)*, vol. 32, Dec. 2014.