Experimental Molecular Communications in Obstacle Rich Fluids

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ABSTRACT

A key potential advantage of molecular communications is the ability of molecules to propagate in complex propagation channels. Here, we experimentally test the information rate in both relatively laminar and turbulent conditions by tracking the information molecules using particle image velocimetry (PIV). A number of obstacle types are placed in the channel and we observe that they do not generally lower the information rate, but may actually improve it in some cases. This is explained by the formation of self-sustaining coherent vortex signal structures with a higher signal-to-noise ratio (SNR), which are caused by obstacles. The initial results demonstrate experimentally that the variety of obstacles tested do not impact data rate and may in some cases enhance it.

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1 INTRODUCTION

Conventional wave-based signals are sensitive to obstacles which cause diffraction and absorption losses. Molecular signals can propagate efficiently through obstacle fields. Previously, in a simple diffusion case, we have shown that molecules can propagate through obstacles more efficiently than EM signals [3, 4]. Other macro-experimental work include chemical modulation and detecting chemical signatures using mass spectrometry [2]. In this work, we attempt to understand in more detail the effect of obstacles on the propagation at high Peclet (Pe $> 10^2$) and Reynolds numbers (Re $> 10^4$), where the effects of sheer stress and turbulence dominate. We use experimental data with particle image velocimetry (PIV) [1] to examine the impact of obstacles on the noise distribution statistics, received signal-to-noise ratio (SNR), and theoretical information rate.

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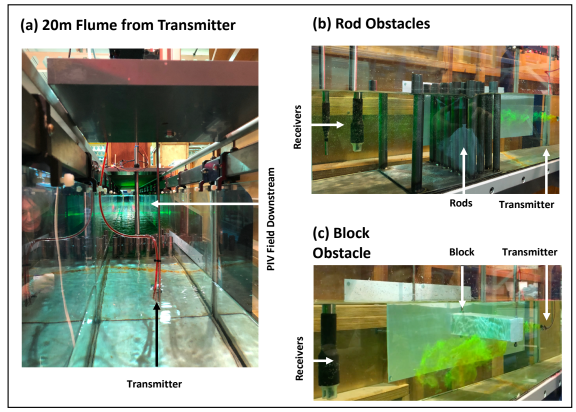


Figure 1: Flow-based molecular communication testbed with obstacles and PIV particle tracing.

2 EXPERIMENTAL SETUP

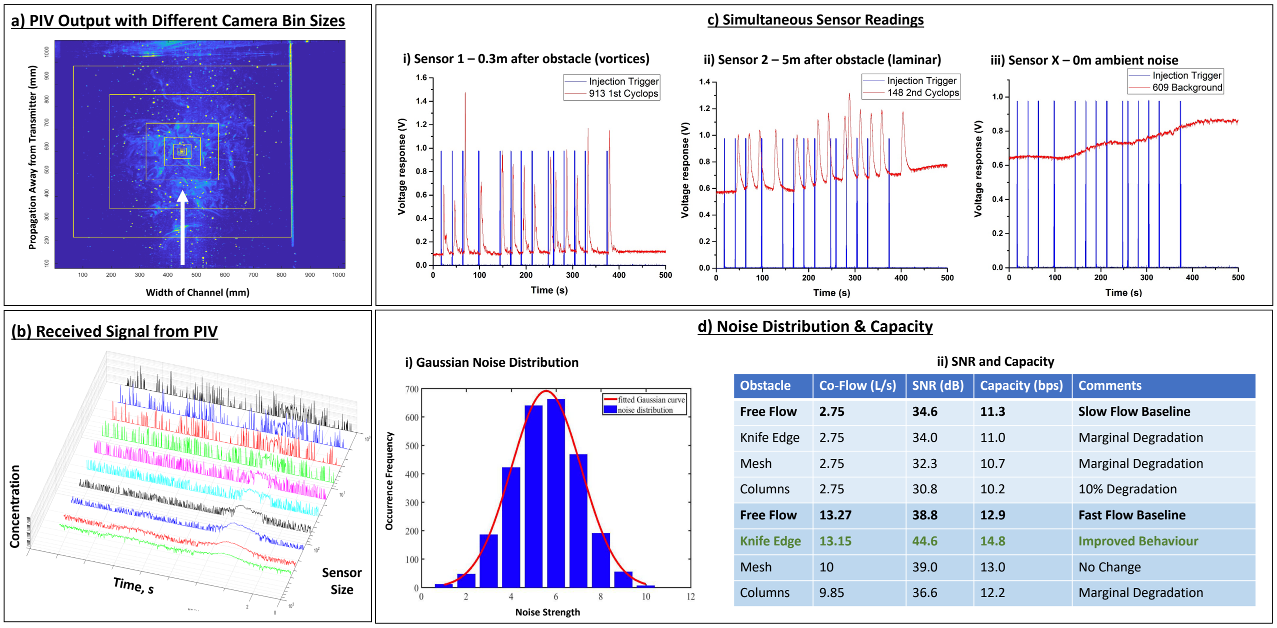
We use a horizontal flow-based channel with variable flow rates of 0-15 L/s and a 1W green laser PIV observation system - see Figure 1a. This can be useful for understanding how information propagates in real world (e.g. underwater rivers and oceans), given that the dimensionless number match between the scenario and experimentation. The procedure involves sending an on-off-keying (OOK) modulation scheme. The molecules are injected as plumes with duration $\tau = 1$s and a time gap of $T = 10$s (see blue spikes in Fig. 2c). We add fluorescent dye to assist detection using PIV. The receiver is either: (1) 90fps camera - images are analysed for luminescence strength as a proxy for concentration, or (2) submersible optical fluorometer - cyclops-7F. Various obstacles are installed to mimic real-world environments (see Figure 1b-c):

- Free flow - where there is no obstacle
- Knife Edge - 30cm×5cm×8cm object partially blocks the flow
- Mesh - dense grid of 3cm×3cm patches creates turbulence
- Columns - a lattice field of 6 rod columns (25cm high and 2.5cm diameter) obstructs the flow.

3 RESULTS

3.1 Sensor Size: Error vs. Rate Trade-off

In Figure 2a, we can see the PIV image, whereby molecules are detected across different catchment area sizes. In Figure 2b, as the receiver size increases, we capture a smoother signal (less noise), but the signal is less sharp, meaning the potential achievable symbol rate is less. Therefore, larger sensors are suitable for high reliability



Obstacle	Co-Flow (L/s)	SNR (dB)	Capacity (bps)	Comments
Free Flow	**2.75**	**34.6**	**11.3**	**Slow Flow Baseline**
Knife Edge	2.75	34.0	11.0	Marginal Degradation
Mesh	2.75	32.3	10.7	Marginal Degradation
Columns	2.75	30.8	10.2	10% Degradation
Free Flow	**13.27**	**38.8**	**12.9**	**Fast Flow Baseline**
Knife Edge	13.15	44.6	14.8	Improved Behaviour
Mesh	10	39.0	13.0	No Change
Columns	9.85	36.6	12.2	Marginal Degradation

Figure 2: (a) PIV output of fluorescent dye and (b) concentration analysis as a function of time and camera capture size. (c) Received concentration at different locations, (d) noise distribution and achievable capacity with different obstacles.

low rate communications, whereas small sensors can achieve a low reliability high rate communication.

3.2 Turbulence and Laminar Flow

We place two optical sensors, one behind the obstacle (0.3m) and one far from the obstacle downstream (5.0m). In Figure 2c, the results (blue spikes - input, red response - received) show that the data can be reliably detected for both sensors, even in heavy turbulence. However, we see erratic amplitude responses that can have a peak to minimum ratio of 2× in sensor 1 at turbulent flow, compared to 1.3x ratio in sensor 2 under more laminar conditions. Sensor X is placed away from the information transmission to give an ambient noise reading for characterisation.

3.3 Noise Distribution & Capacity

We define the detected peak signal power as S and the background noise power as N, and define Shannon capacity as: $\log_2(1 + S/N)$ bits/s (assuming 1 unit of frequency). There are two important initial assumptions: (1) Shannon capacity can be applied directly as the additive noise is Gaussian (see Figure 2d-i); and (2) the signal is only limited by Gaussian noise and ISI can be removed as a means to estimate the upper-bound. The resulting SNR (varying noise) and Shannon capacity in Figure 2d-ii show the following. **Flow Rate:** increasing the rate marginally increases the capacity due to the fact that the signal pulse is less blurred relative to the noise at the receiver. **Single Obstacle:** the knife-edge obstacle does not decrease the capacity, and sometimes increases it, possibly because it generates a more coherent vortex structure after forcing the flow through a narrow opening (see Figure 1c). The post-obstacle vortex structure is due to the fact that we force the flow through a narrower opening with an increased sheer stress from the friction on the obstacle boundary. This creates a vortex structure after the obstacle, which remains quasi-coherent throughout the propagation path and yields a higher SNR. **Multiple Obstacles:** The mesh and rod columns causes turbulence which do not affect the throughput results significantly at the receiver.

4 CONCLUSIONS & FUTURE WORK

In this paper, we experimentally show that obstacles make little impact to the achievable SNR and information rate. In fact, single large obstacles of particular dimensions can increase the data rate by creating a stable vortex structure, which gives rise to increased SNR due to the generated angular momentum. Further work will focus on analysing the impact of ISI and more comprehensive mapping between obstacle fields and achievable information rate.

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