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Molecular Signal Tracking and Detection Methods in Fluid Dynamic Channels

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***Abstract*—This review paper sets out the macro-scale experimental techniques that can translate fluid dynamic knowledge into molecular communication design and practice. Fluid dynamic experiments can capture latent features that allow the receiver to: 1) detect coherent signal structures, and 2) infer flow parameters for optimal decoding. Our paper critically reviews the major molecular signal tracking and detection techniques, spanning optical imaging, acoustic probing, mechanical detectors, and electronic sensors. We offer step-by-step procedures for some of the key methods we have used in previous research outputs, as well as comparative evaluation in terms performance accuracy and practical complexity.**

***Index Terms*—molecular communication; experimentation; macro-scale; fluid dynamics; flow measurement methods; concentration measurement methods;**

I. Introduction

Experimental molecular communications (MC) is critical for a number of research vectors, including: channel characterization [1]–[6], noise characterization for mutual information analysis [7]–[9], and system design (e.g. receiver size, mobility [9]). Experimental work is lacking at the macro-scale ($\geq 1mm$), where molecular signals are subject to a variety of flow associated processes, most of which are dynamic and interrelated. Unlike the mass diffusion dominated regime (typically in micro-scale, $1\mu m - 1mm$, and nano scale, $\leq 1\mu m$), where the channel and noise model is well understood even for different modulation schemes [10]–[17], macro-scale continuum forces make analysis challenging. Macro-scale research is useful for a variety of underwater, gas/oil-pipe networks, chemical engineering, electromagnetically denied, as well as dimensional analysis applications.

Research at macro-scale requires significant undertaking and there is a growing body of work. Theoretical and simulation work on molecular communications with turbulence has shown that the fluid dynamic complexities cannot be ignored [2]. Experimentation is essential to capture realistic variational behaviour in fluid dynamics. It can enable us to: 1) find stable coherent structures in fluids that point towards better modulation design (e.g., generated self-propagating structures to increase symbol rate and transmission range [18]), and 2) infer channel parameters to aid receiver signal decoding (e.g. maximum likelihood estimation [19]).

An overview of experimental molecular communications is given here [20]. Early prototyping experimental work started with tabletop prototypes characterizing experimental throughput [21]–[26] and noise process [4] with crude chemical sensors, which has now advanced to encoding in chemical mixtures [27] with mass spectrometer demodulation. This coincides with parallel work in replicating pheromone signals [28]. In our attempts to understand and improve the achievable mutual information in macro-scale fluid dynamic channels with complex processes, recent work (2018-19) has characterized the evolving information structure in turbulence [3] and tracked info-molecules using fluorescence [5], [29], [30].

A. Key Metrics for Signal Measurement

In all the aforementioned work in macro-scale experimental MC, measuring key attributes of molecular signals are essential. The key attributes are closely related to the manner in which information is modulated to the molecular signal [1]. In concentration-shift-keying (CSK), measuring the concentration of the flow field is important. In pulse-position-modulation (PPM) measuring the time of arrival difference between sequential pulses is important. We can generally either measure the concentration directly, or measure the flow attributes to extract or infer the concentration, as well as other flow attributes. It is worth mentioning that other chemical modulation schemes that encode information in chemical structure (e.g. molecular shift keying) and ratio of chemical mixtures in compounds (e.g. isomer-based shift keying and pheromones), require a mass spectrometer [27] or proprietary electronic nose [28]. We do not cover this latter case, as the chemical structure is generally orthogonal to the fluid dynamics.

In laminar flow, measured concentration or flow attributes can be directly related to laminar flow parameters (e.g. flow speed increases signal-to-noise ratio and throughput [5]). However, in turbulent flow, new processes must be taken into account. In terms of the turbulence structure, the size of the eddies plays a key role in transportation of the information. After initial transmission, large eddies with maximum momentum energy are created and as they propagate, they cascade into numerous smaller eddies (momentum energy into heat). These small eddies do not have significant role in transporting the information as the viscous forces are dominant and this small scale is considered as a lower bound for the molecular communication capacity [3]. There are also other key metrics in turbulence structure such as entrainment

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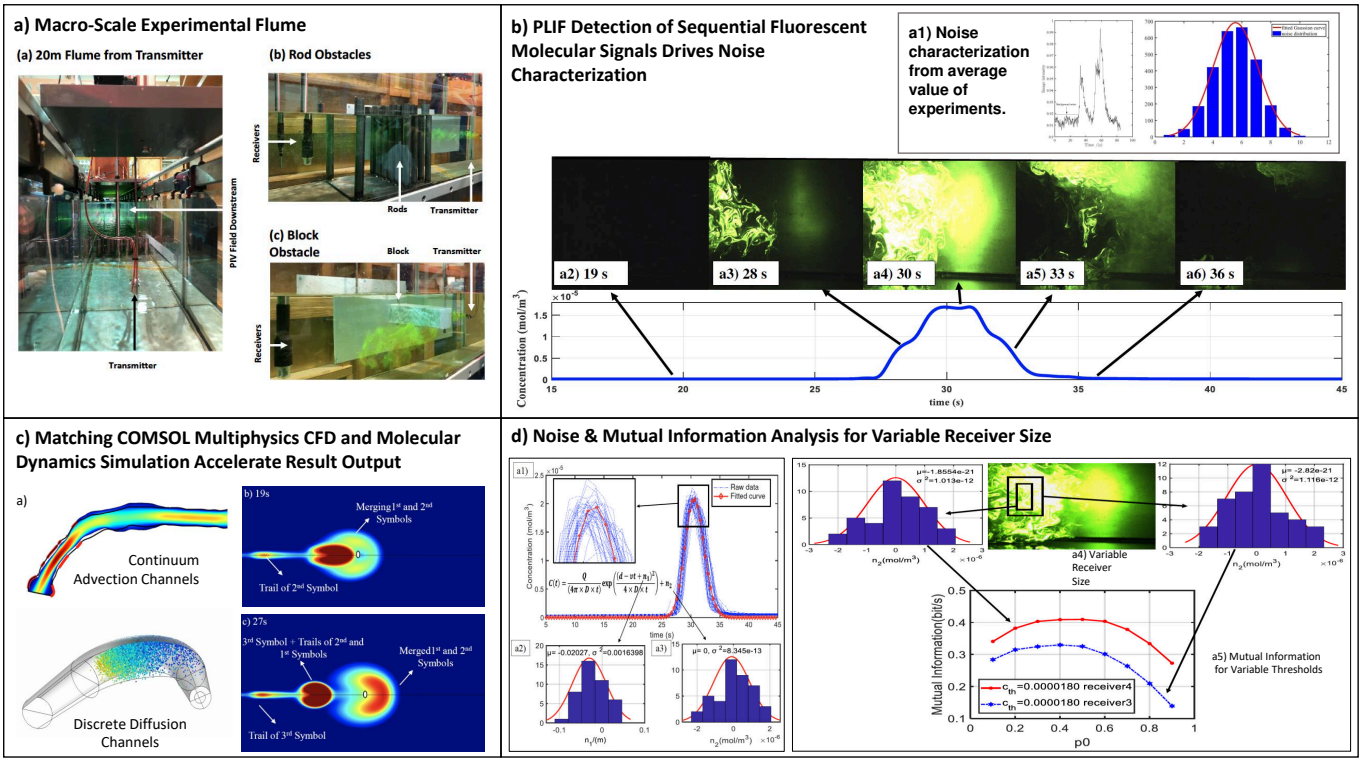

Fig. 1: Macro-scale fluid dynamic platform for MC: a) experimental flume with obstacles and PIV/PLIF molecule tracking, b) PLIF data drives signal and noise quantification, c) multiscale simulation capability accelerates results output, and d) noise and mutual information analysis for variable receiver sizes.

coefficient, frequency spectrum, length scales, etc. which are all embedded in the concept of eddy size and energy cascade.

B. Novelty and Organization of Paper

To the best of our knowledge, this is the first MC paper to detail comprehensive MC signal measurement techniques. We detail a range of flow and concentration measurement techniques ranging from laser based image techniques, ultrasonic profilers, mechanical hot-wire anemometers, to both passive and active electro-chemical sensors. Besides mass spectrometers have been used to demodulate chemical structure information embedding [27], [28], this represents the most comprehensive review of approaches given in existing platforms by the following macro-scale MC groups: Farsad & Eckford et al. [21], Chae et al., [22], Rose et al., [3], [30], Tuccitto et al., [29], and Guo & Thomas et al., [5], [18].

This methods paper builds on the authors' own work over the past 3 years funded by United States Air Force Office for Scientific Research (US AFOSR), Defence Science Technology Laboratory (DSTL), and EC H2020. Together, we have built up macro-scale experimental capability that can faithfully track information molecules, translating fluid dynamic knowledge into molecular communication practice - see Fig. 1. Our setup has been briefly described in Atthanayake et al. [5]. Here, we not only detail the experimental procedure, but also offer a critical review of comparative methods to give the reader a comprehensive guide to macro-scale experimentation.

The paper is organized as follows: In section II, different flow measurement method are discussed. In section III, two concentration measurement methods are discussed. Section IV is the discussion and conclusion.

II. Flow Measurement Methods

A. PIV Method

The most frequently used modern technique for the analysis of flow fields is Particle Image Velocimetry (PIV). PIV is an optical technique used for flow visualization and for the measurement of flow velocities. Our experimental setup is photographed in Fig. 1(a). The method is referred to as non-intrusive since it is not required to use a flow sensor inside the flow field that can potentially alter aspects of the flow to be monitored. The principle of the PIV method is illustrated in Fig.2. Technical details of the methodology are summarized in [31]. The following steps should be done for PIV measurement.

- **Tracer:** The flow is seeded with micron-sized tracer particles. Ideally seeding particles are chosen that are neutrally buoyant. This is required such that the particles always faithfully follow the flow and therewith accurately represent the flow velocity at their locations within the

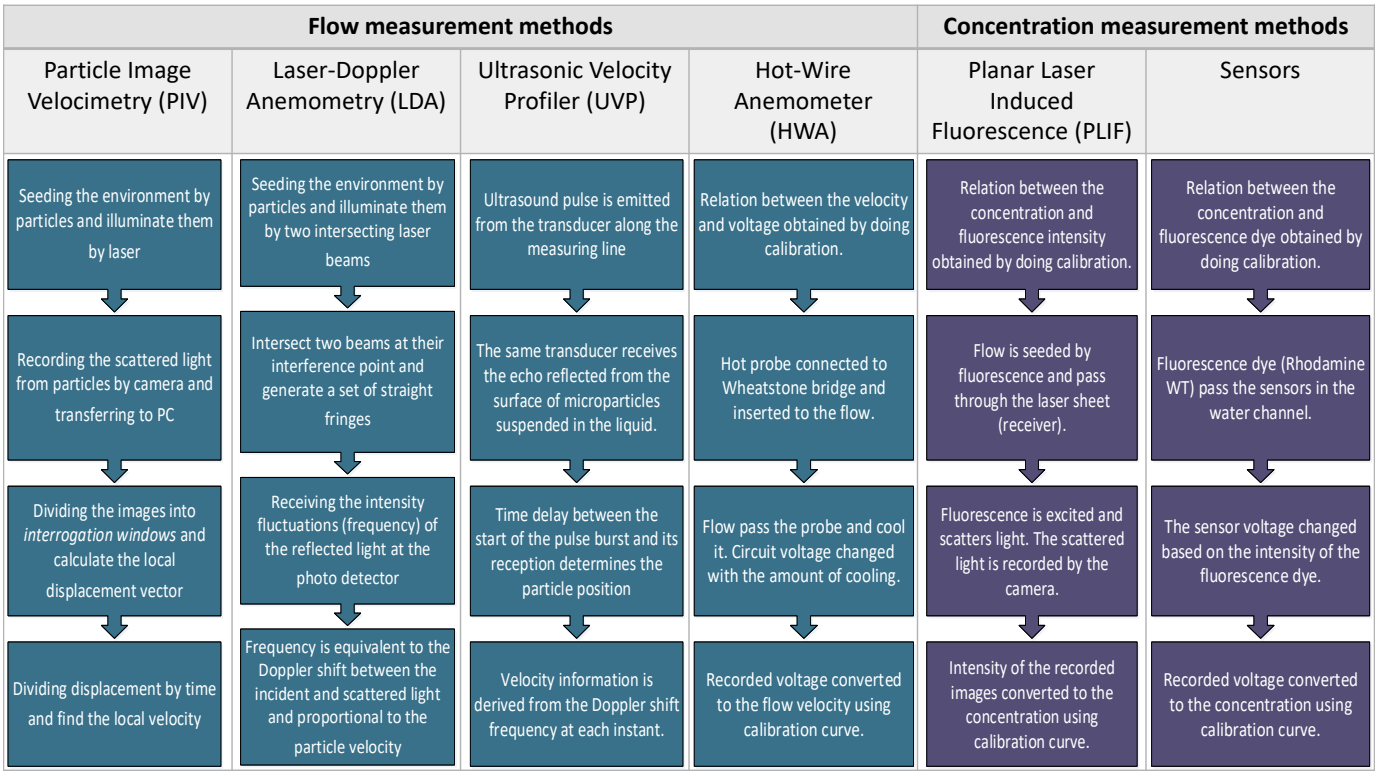

Fig. 2: Block diagram showing step-by-step procedures for measuring the flow and concentration

flow field [32]. In liquids one can use, for instance, hollow-glass spheres as seeding particles, which can be silver-coated to increase their reflectivity as is the case in the experiments of [5], [33]. If the flow is in a gas, then it is not possible to satisfy the requirement for neutral buoyancy and one typically uses, for instance, micron-sized oil droplets as tracer particles.

- **Imaging:** A laser and an optical lens arrangement is used to generate a thin light sheet that intersects the flow as illustrated in Fig. 3. Tracer particles moving within the light sheet become brightly illuminated. Thus, their motion can be recorded by means of a video camera in its image plane.
- **Analysis:** On any two successive video images taken at a short time interval $\Delta t = t' - t$ apart the tracer particles will appear at slightly shifted locations due to their motion while following the flow field. By analyzing from where to where particles have moved within the image plane in the known time interval Δt it is therefore possible to infer the magnitude and the direction of the particle velocity and, therefore, the flow velocity. Once the basic velocity field is known as a function of time other quantities such as time averaged velocities, the vorticity or the turbulence characteristics can be obtained from post-processing of the collected data. An in-depth example showing such results from a PIV study is discussed in [33].

In principle, the most straightforward analysis method for the motion of the seeding particles is called Particle Tracking Velocimetry (PTA), see e.g. [34]–[36]. This method attempts to establish a one-to-one correspondence between particles in each two successive video frames. However, generally it is not possible to establish a one-to-one correspondence at high number densities of particles. The problem is further complicated by the fact that several tracer particles may have moved out of the light sheet or overlap in the time interval Δt between the two video frames.

More sophisticated methodologies have been developed to resolve the problems associated with analyzing the images displaying the seeding particles [31]. The approach taken is to divide the PIV video images into small **interrogation regions** and compare corresponding regions in successive video frames. Each region will contain a number of particles of which some may have a one-to-one correspondence in the two successive frames while others do not. The procedure applied then is to calculate the cross-correlation function for the interrogation region under consideration subject to spatial shifts in the image plane. That particular shift for which the correlation function adopts its maximum is then taken as the direction in which the particles within the small interrogation region have collectively travelled. This direction together with the time interval Δt between the two video frames then defines the magnitude and the direction of the flow velocity at the location of the interrogation region [37]. The Matlab based PIVLab software [38] is a tool for the analysis and post processing of PIV data and it is freely available for download

from the internet.

PIV developed rapidly during the 1990s as increasing computer power became available [39]. PIV equipment is available commercially by companies such as Dantec, LaVision or TSI. In recent years it has become common for laboratories to assemble systems in house from off the shelf components and use PIVLab for the data analysis. The set up in Fig.3 with a single camera can only yield the two velocity components lying within the plane of the light sheet. More recent developments throughout the 2000s are related to making the technique quasi-three dimensional or fully three-dimensional Quasi-three dimensional data can be obtained by using a thicker light sheet together with stereoscopic recording that employs two video cameras. Alternatively one can translate the light sheet back and forth through the liquid to scan a three-dimensional volume at sufficiently high rates to obtain quasi three dimensional data. Fully three-dimensional data can be obtained by means of tomographic / volumetric PIV.

B. PIV in Comparison to Other Methods

There exist alternative methods for velocity monitoring. One technique is Laser-Doppler Anemometry (LDA), also referred to as Laser-Doppler Velocimetry (LDV) [40], other common methods are Hot-Wire Anemomentry (HWA) [41], [42], and Ultrasonic Velocity Profilers (UVP) [43]. However, for most applications the PIV technique has advantages over these other methods.

1) Laser-Doppler Anemometry & Ultrasonic Velocity Profiler : Similar to PIV the LDA and UVP techniques also rely on inferring velocity data from the motion of tracer particles carried along with the flowing medium (the principles of LDA and UVP are the same). A simple one-component LDA, for a single velocity component, crosses two laser beams of collimated (parallel rays), monochromatic and coherent laser light. The overlap region constitutes the measurement volume and at its location within the fluid the velocity is measured. To measure all three velocity components three pairs of laser beams, lying in different planes, are required to cross in an overlapping region. When a tracer particle travels through the measurement volume it scatters light. The velocity information is contained in the laser-light that is scattered from the moving particles. The incoming laser light has a known frequency. The frequency of the light scattered from a tracer particle, and detected by means of a receiver, is Doppler shifted. By comparing the frequency of the incoming light to that of the scattered light it is possible to infer the velocity of the particle. Using a similar approach of comparing transmitted and detected frequencies the UVP technique infers the velocity of the tracer particle on the basis of Doppler shifted ultrasound waves (see Fig. 3).

While the type of PIV system in Fig.3 yields data for the whole light sheet plane, an LDA system only allows the velocity to be monitored at a single location. Albeit it is possible to measure all three velocity components of that particle at that location with a three-component LDA system. In comparison to LDA the UVP technology is more versatile in that it yields velocity data not only at a single location but along the entire straight trajectory along which the transmitted ultrasound beam propagates through the flowing liquid. The UVP technology has a further advantage in that it allows measurements to be conducted in opaque fluids, such as liquid metals [44]. This is possible since the transmission of ultrasound through a liquid does not require the medium to be transparent which is, of course, required for the optical PIV and LDA methods. Similar to PIV the LDA technology is a non-intrusive technique. UVP sensors exist for intrusive and non-intrusive measurement mode.

2) Hot-wire anemometry: Hot-wire anemometry (HWA) dates back to the early 1900s [45]. It is an intrusive technology and requires a small measurement probe to be inserted into the flow field. Similar to the LDA method HWA can only measure the velocity at a single location.

The HWA probe consists of a tin wire, with a typical diameter in the range $1 - 10$ μm and length $0.5 - 2$ mm, attached to two prongs. The wire forms part of an electronic circuit (Wheatstone bridge) as shown in Fig. 3. An electric current flows through the wire and heats it. When the probe is inserted into a flow the motion past the wire results in cooling which, in turn, depends on the flow speed. The electrical circuit yields an output voltage that depends non-linearly on the flow speed past the wire. By determining the output voltage as a function of the flow speed it is possible to calibrate the sensors for any particular fluid environment. Thereafter the sensor can be used in that particular fluid environment to measure the flow speed through the output voltage [42]. To use the HWA probe in a different flow environment it has to be re-calibrated. The calibration curve of a probe can change over time. This is the case, for instance, when gas bubbles form on the probe element. Therefore checking the calibration curve at regular intervals is necessary.

A HWA probe with a single wire is uni-directional and can only detect one flow component. However, there exist probes with two or three wires to measure more than one velocity component. One moreover distinguishes between probes for gases and liquids. The latter have to be more robust and are referred to as hot-film probes.

III. Concentration Measurement Methods

A. Planar laser induced fluorescence (PLIF)

Planar laser induced fluorescence (PLIF) is an optical diagnostics technique that can measure the concentration of a fluorescent tracer dye as it gets carried along and diluted in a fluid flow. A tracer frequently used is Rhodamine 6G; this has peak adsorption at a wavelength of 532 nm and peak emission at around 560 nm [46]. Our example experimental data visualization and analysis of the received signal is given in Fig. 1(b-d).

Similar to PIV the PLIF technique requires a cross section of the flow to be intersected by a laser light sheet as illustrated in Fig.3. Liquid within the light sheet containing amounts of the tracer fluoresces. The fluorescence intensity is primarily

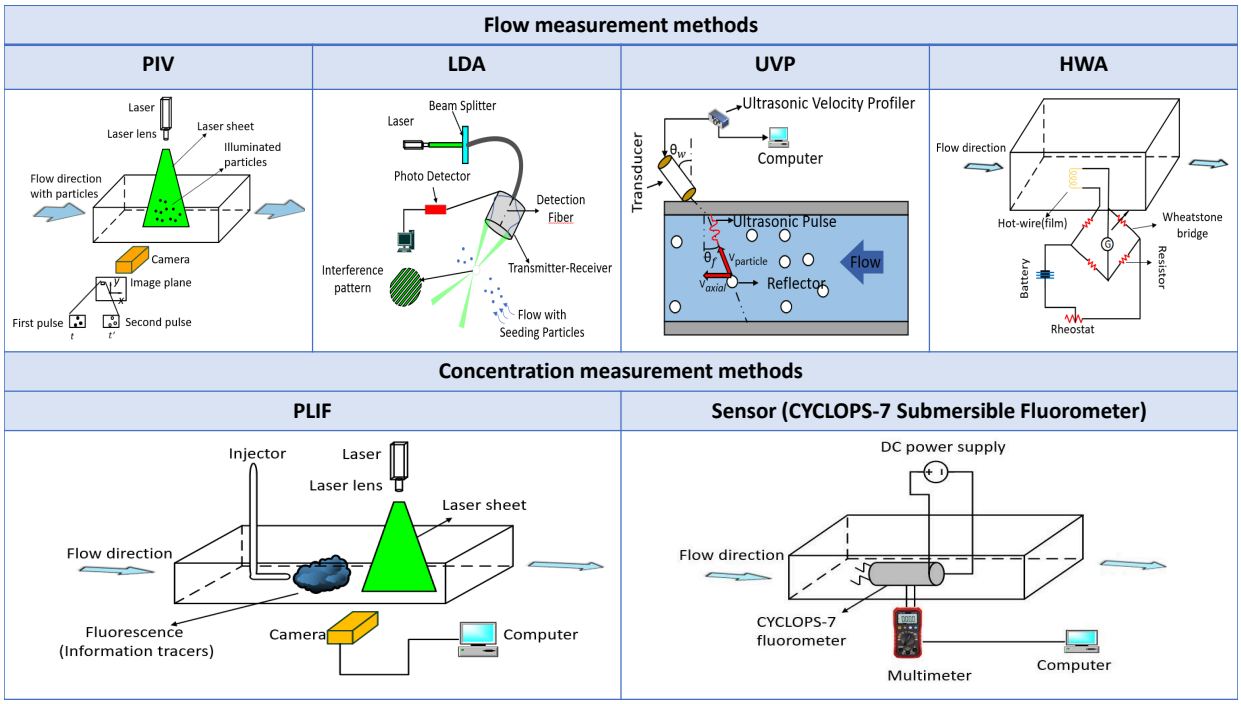

Fig. 3: Schematic of different flow and concentration measurements

dependent on the tracer concentration but it is also affected by ambient factors such as the temperature. It is required to perform a calibration for the fluorescence intensity as a function of the tracer-dye concentration in the environment where measurements are to be performed to enable a quantitative analysis of the concentration distribution in video images recorded by a CCD camera. PLIF can be combined with PIV to concurrently obtain concentration and velocity data.

The viewing direction of the camera is required to be perpendicular to the light sheet to avoid any parallax data bias. A notch filter should be positioned in front of the camera to remove light not required for the data analysis. In the case of Rhodamine 6G, for instance, light below 550 nm should filtered out such that only the light from the emission peak at 560 nm is detected by the camera. For further details associated with the calibration process refer to, for instance, [47].

In typical signal-transmission experiments a known amount of liquid, containing a certain concentration of the fluorescent tracer, can be released from, for instance, a small nozzle within the flow field. The fluorescent liquid is then viewed as representing information carrying particles released by a sender. Thus, the fluorescence pattern that becomes visible within the light sheet provides a visual representation of the dynamic behaviour of the information-carrying liquid particles as they get carried along in the flow and, facilitated by the action of eddies and turbulent flow fluctuations, mix with ambient liquid.

B. *Sensors*

An alternative method for measuring the concentration of tracers contained in a liquid is provided by a variety of active electronic (e.g. electronic nose) and passive optical sensors. Using sensors is straightforward and has the advantage of not requiring a laser. However, the disadvantage of sensors in comparison to laser-based methods is that they are intrusive and have to be submersed in the flow field. One commonly used sensor is the Turner Designs CYCLOPS-7 Submersible Fluorometer [48]. Rhodamine WT, where WT stands for 'water tracing', is often used as the fluorescent tracer but there exist others. The sensor displays and records the level of the tracer concentration in terms of an output voltage. The output voltage increases linearly with the concentration level in the measurable range of the fluorometer. For the calibration procedure the sensor is submersed in water contained in a beaker. Defined amounts of the tracer are successively added to the liquid and the associated output voltages for the known concentrations are recorded to yield the calibration curve.

IV. Discussions & Conclusions

A. *Experimental Data Aids Communication Understanding*

Noise characterization is important for understanding the achievable mutual information in these complex signaling environments [7]–[9]. Analytical noise expressions from mass diffusion channels for concentration modulation [10], [12] and timing modulation [13]–[15] are well understood. By modeling the noise empirically using our reviewed experimental techniques, one is able to calculate the mutual information

TABLE I: Summary of features of flow and concentration measurement methods. Equipment needed for running experiment and websites for purchasing those equipment.

	Flow measurement methods			
	PIV	LDA	UVP	HWA
Features	• Non-intrusive • Currently normally gives velocity in 2D plane but and 3D methods are now becoming available • Low resolution • Hazardous (laser) • Requires transparent liquid	• Non-intrusive • Velocity in single point only • High resolution • Hazardous (laser) • Requires transparent liquid	• Non-intrusive • One velocity component only, but yields data along a line in flow field • Medium resolution • Can be applied to opaque liquids	• Intrusive • Velocity in single point only • High resolution • Can be applied to opaque liquids
Equipment	• Laser (Pulsed frequency doubled Nd: YAG at 532 nm wavelength) • Camera (High-speed CMOS camera) • Seeding particles (Hollow glass spheres, Polystyrene, Oxygen bubbles) • External hard drives	• Laser (Pulsed frequency doubled Nd: YAG at 532 nm wavelength) • Camera (High-speed CMOS camera) • Seeding particles (Hollow glass spheres, Polystyrene, Oxygen bubbles) • External hard drives	• UVP package (Transducer, Measuring unit, and Software) • Other accessories (Coupling gel, Acoustic reflectors, Transducer holder, Transducer cable extension)	• HWA package (Probes with probe support and cabling, CTA anemometer, Signal conditioner, and A/D converter)
Website	dantecdynamics.com ; wd.com	dantecdynamics.com ; wd.com	met-flow.com	dantecdynamics.com
	Concentration measurement methods			
	PLIF		Sensor	
Features	• Non-intrusive • Yields concentration distribution in a 2D plane • Hazardous (laser) • Requires transparent liquids		• Intrusive • Yields concentration in single point only • Can be applied to opaque liquids	
Equipment	• Laser (Pulsed frequency doubled Nd: YAG at 532 nm wavelength) • Camera (High-speed CMOS camera) • Notch filter for the camera (OD 6.0) • Seeding particles(Rhodamine 6G) • External hard drive		• CYCLOPS-7 Analog Detector • CYCLOPS-7 Documentation Kit • Calibration Certificate • DC Power Supply • Multimeter	
Website	dantecdynamics.com ; wd.com		turnerdesigns.com	

either analytically for Gaussian distributed noise [5], [9], or numerically via non-Gaussian distributed noise [49]. An example of PLIF experimental signals is given in see Fig. 1(b), which is then used to complete accelerated data collection in see Fig. 1(c) using COMSOL [50]. Extracting both the additive and jitter noise distribution can be conducted and further analysis of the mutual information can be conducted to understand the optimal transmission strategy to maximize the mutual information.

B. Experimental Recommended Practice

Lasers have potential hazards to the human eye and skin from both direct and scattered beam exposure. The radiant power of lasers used in PIV generally have around 1000 mW with a wavelength of 532 nm and a beam diameter of 1mm (for optimal water transmission). To understand safety, we calculate the maximum permissible exposure (MPE), which is the highest power or energy density (in W/cm^2 or J/cm^2) of a light source that is considered safe. It is usually about 10% of the dose that has a 50% chance of creating damage under worst-case conditions. The MPE is measured at the cornea of the human eye or at the skin, for a given wavelength and exposure time. Our beam divergence is 3 milli-radians (0.003 radians) and 25 W/m^2 is the eye MPE for a single accidental exposure to a continuous wave (CW) laser beam from 400 to 700 nm. The laser delivery system produces a beam plane which is 30cm wide, aligned perpendicular to the long axis of the fluid channel. To counter this, the laser area must be fitted into a wooden box structure to cover the Nominal Ocular Hazard Distance (NOHD):

$$\text{NOHD} = \frac{\sqrt{\frac{4\times\text{radiant power}}{\pi\times\text{MPE}}} - \text{initial beam diameter}}{\text{beam divergence}}, \quad (1)$$

which is the distance from the source at which the intensity or the energy per surface unit becomes lower than the MPE on the cornea and on the skin.

C. Conclusions

In this paper, different flow and concentration measurement methods for tracking and detection of molecular signals are reviewed for their performances and their procedural steps detailed. Fluid dynamic experiments in molecular communication generally aim to measure: 1) flow parameters that are proxy for the channel parameters to aid receiver side

signal processing (e.g. maximum likelihood detection), and 2) coherent structures (e.g. vortex rings) that are a proxy for modulate information.

For measuring the flow parameters such as velocity spectrum, energy spectrum, and eddy size across various length scales and high resolution outputs are necessary, so the HWA and UVP methods are advised. Detecting coherent structures which contain modulated information especially in 2D or 3D in flow field requires a non-intrusive methods so the PIV is mostly practical in that sense. Measuring the concentration by means of the sensors is straightforward, but they are intrusive and measure the concentration only at a point. So, to avoid loosing information spatially, the PLIF or similar imaging method should be used. A brief overview of all methods has been presented in Table I for better comparing off all methods.

Finally, the key message is that often a combination of methods is needed to capture both the key molecular signal information (e.g. concentration measurement) and also track the channel parameters that caused it (e.g. flow measurement).

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