Study on Viral Aerosol Transmission and Detection

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***Abstract*—We propose to use the process of disease spread in the atmosphere as an engineering problem in this study. When long-distance virus-laden droplets are transported by airflows, aerosol transmission—one of the most significant viral modes that does not require physical contact—occurs. In this research, we study the transit of these droplets as an uncontrollable molecular communication problem over the transmission source, whereas biosensors can be used to produce a powerful receiver. As a result, we offer a thorough system model construction and derive a thorough mathematical model for the transmission channel under particular constraints and boundary conditions.Both continuous sources, such as breathing and jets, and spontaneous sources, such as coughing and sneezing, have their system response determined. We assumed a receiver architecture consisting of the transmitter and channel, as well as an air sampler and a silicon nanowire field-effect transistor. In order to minimize the possibility of the corresponding missed detection and optimize the decision rule for likelihood, we then formulate a detection issue. Finally, to demonstrate the impact of performance-influencing parameters and to merely validate the viability of the suggested configuration in relevant applications, we present certain numerical results.**

***Index Terms*—Communication through breath, aerosol transmission, virus detection, molecular communication, nanonetworks, channel modeling, molecular receiver, advection diffusion channel.**

I. Introduction

Molecular communication (MC) is an expanding branch of research that focuses on the communication mechanisms involving biological components. Unlike conventional wireless communication, which encodes and sends electromagnetic signals to share information, MC uses molecules as signalling sources. The scientific community has only lately become aware of this phenomenon, even though the majority of living things naturally use it as a communication channel. This interest and the advancement of the field's study are attributed to recent advancements in nanotechnology and the introduction of nanoscale biosensors or nanotechnologies [1]. Their potential is constrained by the existing nanotechnology's small size, limited energy sources, memory, and processing power. Thus, many nanotechnologies need to work together to do complex tasks, which is where the concept of MC comes in handy. MC provides this connection, allowing the development of a cooperative network of nanotechnology, even though existing electromagnetic and optical technologies are unable to establish links between nanotechnology [2].This branch of study enables the development of artificial networks that can replicate biological networks inside and outside the human body. In addition to helping us understand the workings of complex biological systems such as the brain, this will help treat many diseases and disorders caused by faulty internal communication channels [3]. These advancements are therefore expected to be important for ecological, biomedical, and manufacturing applications [1]. Novel biomedical applications include neural network modelling, developing ICT-inspired therapeutics [3], and intelligent drug delivery [4]. Apart from biological applications, MC has also been studied from a communications standpoint, which focuses on the design of efficient receivers, evaluation of modulation programs, and coding principles [5]. It should be noted that the existing solutions for traditional communication are difficult to adapt to MC settings due to the process's intricacy. Range restrictions that allow nanotechnology to communicate over short distances (less than a few micrometres), significant propagation delays, non-stationary signal-dependent noise, issues with molecule reactivity that result in high loss rates, memory limitations, power constraints, and the relationship between nanotechnology and bio-nanotechnology are some of the issues with MC [1]. These challenges have a significant impact on the current and future directions of this field's research. Furthermore, a variety of new research options have been made possible by these nanoscale sensing structures' capacity to interact with biological organisms, such as bacteria. For instance, rather than using synthetic chemicals and molecules, bacterial compounds serve as messengers for communication amongst bacterial colonies, with receptor bacteria emitting light in reaction to molecules they receive [6]. Researchers have worked to comprehend, replicate, and interface with current biological processes and systems in addition to applications at the micro and macro

levels. In this paper, we suggest a novel aspect of MC that centres on the aerosol-mediated transmission of illnesses and infections. Droplets containing viruses that are suspended in the atmosphere for extended periods of time are known as viral aerosols [7]. Aerosol transmission is the term for the movement of these particles through the environment due to molecular diffusion and wind. The human population is greatly impacted by the widespread spread of disease caused by this virus transmission. Numerous viruses, including the influenza A virus [8], the severe acute respiratory syndrome (SARS) virus [9], the lyssavirus [10], the rabies [11], and numerous other pandemics, have been demonstrated to spread primarily by aerosols. The message-bearing entities in this specific environment cannot be modulated, and the message cannot be implanted as intended, in contrast to standard MC research. Nonetheless, we think that the virus-contaminated air that an infected individual exhales can contain valuable information, and we must build our receiver to extract this information. In scenarios with a large human population, the importance of this suggested study dimension is further emphasized. Mass gatherings are frequently observed when people congregate for social, religious, recreational, or athletic purposes. Numerous individuals from various areas congregate during these events, which increases the danger of disease transmission and the introduction of newly emerging and reemerging illnesses to the gathering site. According to [12]–[15], there is a higher chance of illness transmission during mass gatherings. This issue can be resolved with the use of the detection system suggested in this study. Diseases can be considerably stopped from spreading if an effective detection system is set up at the entrance to gathering places, such as train stations and airports, and the prospective hosts of endemics and diseases are identified and treated before they join the crowd. Furthermore, if precise models for virus transport and dynamics can be developed, a blind localization problem that aids in locating disease sites can be developed. The dynamics of virus transport must therefore be characterized and analyzed, as this work has done, in order to be able to take any preventive actions against the spread of disease.

II. SYSTEM OVERVIEW

This section provides a brief explanation of the basic architecture of a single source viral aerosol transmission system. The proposed system consists of three major components. The first is the infected individual who transmits the infection; this individual is referred to as the transmitter for the remainder of the paper. The path via which the virus spreads through aerosols is the second component. The gearbox can be exposed to airflow or simulated wind. The third component is the receiver side, which looks for information about the infection or illness. This research aims to retrieve viral information from aerosols exhaled from the respiratory tracts of infected individuals, as illustrated in Figure 1. Indoors, where artificial airflow with a preset velocity may be produced, the experiment is carried out to drive the particles towards the detector. Please note that the experimental configuration under consideration is very close to a real-world situation where wind causes virus droplets to spread. Thus, in addition to bio-monitoring applications, the models created in this work can be applied to qualitative and quantitative studies of infection transmission.

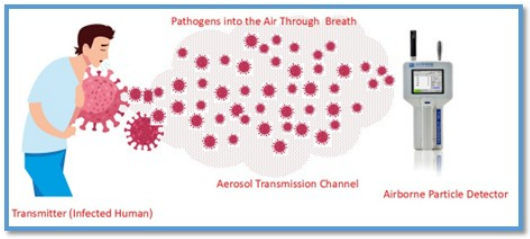

Fig. 1. Aerosol transmission Description.

III. SYSTEM MODELING

Examining each system block in Figure 2 separately is the aim of this section. The transmitter is the first part of the system, and then the detector and the physical channel with additive noise. In the next subsections, the complete mathematical modelling of the different parts of the system is described.

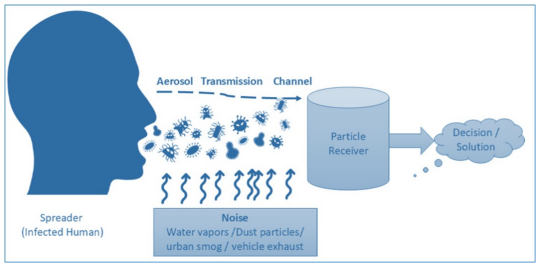

Fig. 2. Block Diagram.

A. Spreader

Microorganisms are thought to be released into the atmosphere by the diseased person's breath. Each breath should take no more than 4.98 seconds, as an adult's normal breathing rate is 12–16 breaths per minute [24]. It may take several minutes for a signal to reach a receiver a few meters away due to the significantly slower transmission speed of chemical signalling compared to wireless communication. As a result, the transmission process ensures that the experiment's duration is within minutes. Because the time within breaths (or exhalation time specifically) is too short in relation to the experiment's duration, which is of the order of several minutes, the differences in the emission process caused by exhalation can be averaged out and the process can be roughly described as a continuous and constant emission process. We expect the average rate to stay constant throughout the experiment (a few minutes at most), even if the emission rate may change over time. Although it is advantageous if the emission rate variations can be incorporated into the system design, it is difficult to find a deterministic or stochastic model in the literature that

can explain these variations. The bulk of empirical studies on this subject are based on collecting breath samples that last anywhere from a few minutes (about half an hour) to hours and recording the cumulative effect. It is uncertain whether the current technology can evaluate the short-term variations in the emission rate per second. Since the average emission rate, or Q g/sec, is constant, we depict the input signal as a continuous process. Impulsive jets are frequently caused by breathing, albeit their consistency cannot be assured. For the purpose of mimicking the input signal, the duration of an experiment or the temporal characteristics of the application are essential. For some purposes, such as comprehending the spread of disease or detecting it in particular environments, the steady state response is sufficient. Applications that need fine-grained data for decision-making require a transitory response. Taking into account both time and spatial dynamics, this section discusses transient analysis for breathing, jet sources, and steady state response. For transitory analysis, the input is represented differently. An instantaneous jet source that releases As aerosols into the atmosphere is thought to be a single cough or sneeze. When someone sneezes or coughs at time t = 0 while standing at position [0,0,H] in any area with a height of approximately H, the source is represented as [18],

$$S_s = A_s\delta(x)\delta(y)\delta(z-H)\delta(t) \tag{1}$$

where, As is the sneezing person's aerosol. Similarly, during breathing, the person continuously releases aerosols with a particular flow rate Ab. If the person entered the room or experimental setting at time t = 0 and then stood at the same location [0,0,H] once more, the source is represented as follows:

$$S_b = A_b\delta(x)\delta(y)\delta(z-H)u(t) \tag{2}$$

where, Ab is the breathing person's aerosol. Since a person who sneezes is also breathing, the definition of input signal should include both continuous and jet sources. Assuming that these two emissions are unrelated to one other, we define the final input signal as follows:

$$S_t = S_S + S_b \tag{3}$$

Due to their independence from one another, if multiple people are present in the room at different locations, the final input signal is just the total of their emissions. In addition to the emission rate, the size of the aerosol droplets affects the communication performance.

B. Particle Receiver

To distinguish between an infected and healthy person, we propose a detection technique. Once a certain number of infections have been released into the environment and have passed through the molecular channel, the receiver acts as an absorbing surface, absorbing the bulk of the pathogen-laden droplets. In Figure 3, the particle receiver architecture is displayed. The three main blocks' details are shown below.

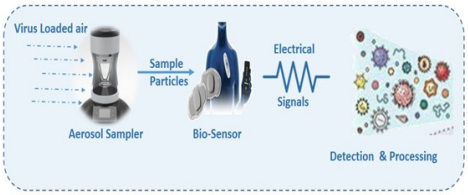

Fig. 3. Architecture of Particle Receiver.

- Aerosol Sampler: Many techniques have been developed to collect suspended air particles. The aerosol tester, the front end of our receiver, controls the air sample rate. Despite the existence of several other approaches, the tester proposed in this receiver design is based on the electrostatic precipitation concept, which is not only commercially available but also allows sampling of particles as fine as 2–100 nm. The sensitivity of the sampler in terms of sampling nano-sized particles is rather significant because the diameter of bacteria and viruses can typically be on the order of nanometers, and droplet sizes are on the scale of a few micrometres. The construction of the electrostatic air sampler is depicted in Figure 4. The two main components of the sampler are the charged electrode and the ionizer. The ionizer produces a negative charge on the air particles that proceed to the next chamber and collect on the positively charged electrode after they have been repulsed by the outer negatively charged boundary. The sampler's performance is evaluated based on how well it collects data. According to [16], commercial electrostatic aerosol samplers can attain collection efficiency of 80 to 90%. In the rest of the work, sampler efficiency is represented by ξ.

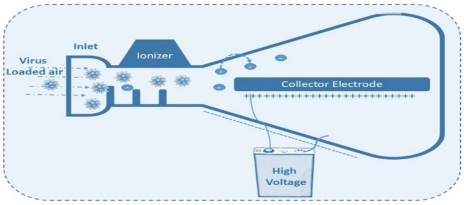

Fig. 4. The Electrostatic Air Sampler's Construction

- Biosensor: A biosensor is an advanced analytical instrument that transforms biological interactions into electrical signals. These tools are crucial for determining

and measuring the concentrations of various biological components. Even without direct contact with a biological system, a biosensor can identify biologically significant factors. Biosensors work by attaching a transducer to a biological sensing component, including nucleic acids, enzymes, or antibodies. The transducer acts as a detector by converting the biological link into an electrical signal. The first practical biosensors, which were electrochemical sensors designed to assess different analytes, laid the groundwork for the current development of biosensing technology [17]. A biosensor is basically composed of three fundamental components, as seen in Figure 5. The first is the sensor, which is a sensitive biological material like microorganisms or tissues. The second component, the transducer, detects the interaction between the analyte and the biological element using methods such as optical or electrochemical detection. Finally, the third component consists of the associated electronics that process the signal and display the results.

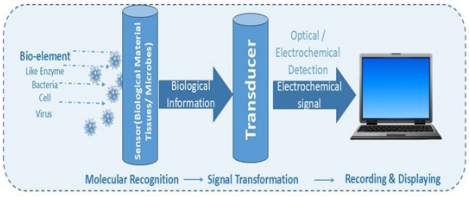

Fig. 5. Biosensor Working

TABLE I
AEROSOL BIOSENSOR EXPERIMENTAL DATA

Parameter	Sensor type	Tentative value	Units
Detection Limit	Electrochemical	5	Ppb
Sensitivity	Optical	0.28	(A.U.)/ppb
Response Time	Piezoelectric	15	sec
Choosiness	Electrochemical	98	%
Constancy (7 Days)	Electrochemical	90	%

Table 1 displays a number of aerosol biosensors with a focus on detection capabilities, stability, sensitivity, and reaction time. The main discoveries are: For trace-level detection, electrochemical sensors are incredibly sensitive; they can pick up particles as small as 5 parts per billion. Even at low analyte concentrations, optical (fluorescence-based) biosensors can provide a strong signal due to their high sensitivity of 0.2 A.U./ppb (Arbitrary Units). Piezoelectric sensors, such the Quartz Crystal Microbalance, or QCM, are helpful for real-time monitoring because they reply in 15 seconds. The ability of enzyme-based electrochemical sensors to consistently distinguish the target aerosol from other airborne substances is demonstrated by their 98% selectivity. Optical (SPR-based) sensors vary by ±3% over multiple trials, ensuring reliable performance throughout repeated tests. Electrochemical sensors retain 90% of their initial signal after seven days, suggesting prolonged use with minimal calibration requirements. Low interference ensures that data from all kinds of sensors remain constant despite variations in temperature, humidity, and air composition.
Comparison of Viral Aerosol Biosensors:

- For real-time monitoring and extremely low detection limits, electrochemical biosensors are superb.
- In public spaces, optical biosensors are effective for rapidly screening for flu-like viruses.
- Hospitals and quarantine facilities can benefit from SPR-based biosensors since they provide the highest selectivity and accuracy.

TABLE II
COMPARISON OF VIRAL AEROSOL BIOSENSORS

Virus Type	Best Sensor Type	Key Advantage	Limitations
COVID-19 (SARS-CoV-2)	Electrochemical (EIS)	High sensitivity, real-time detection	Needs trained operators
Influenza A (H1N1)	Optical (Fluorescence)	Fast response, non-invasive	Sensitive to environmental factors
SARS-CoV	SPR-based Immunosensor	High selectivity, reliable readings	Expensive setup, slower processing

IV. AEROSOL TRANSMISSION CHANNEL

A precise channel model is necessary for both theoretical study and the development of the optimal receiver/detector. The model describes the dynamics that drive the message from the source to the receiving equipment. The (artificial) wind acts as the carrier, carrying aerosols to distant devices. Aerosol motion is a form of fluid flow and is primarily caused by two processes: advection and diffusion. Advection, also known as convection, is caused by the wind, which is defined by wind velocity.

There are two types of diffusion: molecular diffusion and turbulent diffusion. The thermal motions brought on by molecules' natural need to find equilibrium are referred to as molecular diffusion. Conversely, turbulent diffusion describes the mass transfer or diffusion brought on by turbulent eddies. The diffusion process is described by the diffusivity coefficient, and the flow variations caused by molecular diffusion can be roughly estimated using Fick's law.

It should be noted that, from the perspective of aerosol communication presented in this work, where advection plays a large role, molecular diffusion is often ignored in the modelling process and is negligible in comparison to turbulent diffusion. Conversely, diffusion-based MC[1] focuses exclusively on molecular diffusion and is primarily grounded in Fick's equation. These differences in the fluid dynamics lead to entirely distinct models for the two channels. Because of the slight fluctuations in density in the flow field, it is also assumed that the flow is incompressible to make analysis easier.

Since the aberrant motions of molecules are the cause of this communication, it is micro-scale. On the other hand, aerosol communication—the macro-scale movement of microparticles over greater distances—can be explained by dispersion models. Moreover, bioaerosol mobility in the atmosphere is mostly governed by advection and turbulent diffusion, with molecular diffusion having a

little impact. The wind causes advection, while eddies create turbulent diffusion. Since the eddy diffusivity coefficient is much higher in dispersion models, the molecular diffusivity coefficient can be ignored.

The objective of the mathematical model is to determine the aerosol concentration at different stages of the system.To do this, we use the law of mass conservation to characterize the system dynamics that result from the addition of one or more aerosol sources. These aerosols are occasionally eliminated from the system using inactivation techniques such receiver-side collection or ground absorption. We analyze the behaviour of aerosol mobility in both spatial and temporal domains using the well-known Navier-Stokes equation, which can be combined with the continuity equation to formally characterize the system. These partial differential equations must be solved under certain initial and boundary conditions in order to get an expression for aerosol concentration, which is typically a difficult process [19].

A. Deterministic Modeling

Deterministic models of the channel are obtained by solving the aforementioned sets of partial differential equations (Navier-Stokes and continuity equations) while considering boundary and beginning conditions. Both transient analysis and steady state are potential results for deterministic modelling. By estimating breathing as a continuous, constant source at a fixed point and establishing a simplified set of boundary constraints, the Gaussian Plume model [19] offers the solution for the former. On the downwind direction (the line of sight from source to machine), the concentration profile in this model takes on a Gaussian shape along the centerline at a specific point. Additionally, as we go away from the source and downwind, the standard deviation increases. As a result, it looks like a set of Gaussian curves (in the y-z plane) of increasing variance stacked along the x-axis as we move away from the source and toward the detector direction. In the context of the transitory analysis, we investigate the effects of a single sneeze, cough, or breath on focus. This problem can be solved using the Gaussian Puff model.

B. Stochastic Modeling

The intrinsic unpredictability of fluid motion complicates accurate particle concentration calculations. Furthermore, the non-linear behaviour and flow-dependent nature of turbulent motion make it extremely difficult to develop a tractable ideal model [20]–[22]. Here, the most straightforward approach is to use a random walk model, while the most challenging is to solve a set of stochastic differential equations. Deriving a near form formula or the density function for this random process is challenging. We then resort to tracing the movement of the fluid constituents at each time point in order to reproduce the turbulent flow. A random velocity component consisting of drift (mean) and stochastic variations is what causes particle dispersion. The simplified Gaussian plume model provides an analytical solution with a mean concentration profile. However, in order to accurately represent fluid flow in physical systems, stochastic models are required. Two popular computational models based on fluid flow needs are Lagrangian and Eulerian. Particles are tracked and tagged using the Lagrangian approach to monitor their position, speed, and other pertinent parameters. The Eulerian approach, on the other hand, considers a fixed frame of reference or control volume that is employed to monitor the properties of the fluid. Instead of tracking the properties of individual particles, the Eulerian approach tracks how its markers behave when fluid passes over them. Consequently, the computation for every sample instant entails resolving the appropriate differential equations for the designated locations.

In the case of statistical analysis, the same two techniques are applied again. The Eulerian approach is based on a set of instantaneous differential equations [20]–[22], from which further equations determining the known statistics (mean and variance of velocity) are generated. Models for unknown values based on known statistics are already available to arrive at a set of closed equations for these unknowns. The Lagrangian approach locates particles using conservation equations and the statistical description of fluid variables such as velocity.

V. VIRAL AEROSOL TRANSMISSION AND DETECTION

In this section, we look at a case study of detecting a virus from the aerosol of tainted human breath. To understand the implications of the channel behaviour of the proposed communication system, we need to understand the ”symbol” analogy to the conventional communication system. In this case, the aerosol concentration from a single source over time defines the symbol that represents the pertinent information. Similar to communication systems, where the impulse response describes the channel behaviour, we study an impulse source in the spatiotemporal dimension. This is accomplished by supposing that an instantaneous transmitter of height H is located at the origin at time t = 0 and releases a sizable amount of aerosols Q into the atmosphere. The aerosol concentration is measured at various milliseconds (ms) and computed using the Gaussian puff model. It is believed that the crosswind direction has the least influence, whereas the x-axis, or downwind direction, has the biggest wind component. We observed that during specific milliseconds, the aerosol particles are concentrated around the origin, or source. As they go downwind, other aerosol samples spread out over the spatial region with lower peak values. Thus, the breath transmission occurs via a long-tail dispersive fading channel, causing interference and lag between the previous and current system symbols. In other words, many recognized systems may experience

Inter Symbol Interference (ISI) because to the frequency-selective characteristics of the channel.

Viral aerosols can range in size from 0.1 to 5 μm and have life lengths of up to 72 hours, depending on the environment. Viral aerosols can be detected with limits as low as one copy/mL in five to twenty minutes using detection techniques (such as electrochemical, optical, and QCM-based biosensors). Viral viability is reduced by high temperatures ($> 30°$C), whereas transmission is increased by humidity (40–60%). As indicated in Table 3, the 95–99% selectivity provided by qRT-PCR and biosensors ensures accurate identification of airborne viruses.

TABLE III
VIRAL AEROSOL TRANSMISSION AND DETECTION – EXPERIMENTAL DATA

Parameter	Tentative value	Units	Dimension Method	Meaning
Particle Size (Virus-Laden Droplets)	0.1-5	μm	Aerosol Particle Sizing (APS), Scanning Electron Microscopy (SEM)	Evaluates the stability and risk of propagation of airborne viruses.
Airborne Survival Time	3-72	Hours	Controlled Chamber Studies, Viral Culture Assays	Virus capability subject to humidity, temperature, and UV exposure.
Detection Limit (Biosensor Sensitivity)	1-10	Copies/mL	Electrochemical, Optical	Lower detection limits permit primary contagion detection.
Response Time of Biosensors	5-20	Minutes	QCM, Amperometry, Fluorescence	Quick detection is critical for real-time monitoring.
Selectivity (False Positives/Negatives)	95-99	%	RT-PCR vs. Biosensors Comparison	Guarantees correct viral detection, avoiding misdiagnoses.
Stability of Detection Methods	85-95	% (over 7 days)	Continuous Signal Monitoring	Long-term consistency for epidemic surveillance.
Effect of Humidity on Transmission	Higher at 40–60% RH	%	Environmental Chamber Testing	Restrained humidity increases aerosol stability.
Impact of Temperature on Virus Viability	Reduces above 30°C	°C	Controlled Temperature Experiments	High temperatures reduce virus survival.
Airborne Viral Load in Infected Environments	$10^2 - 10^5$	RNA copies/m³	Air Sampling	qRT-PCR
Indicates risk level in closed spaces.				

We also find that after the infected individual leaves the test room, the concentration of viral aerosol remains detectable for a longer duration. Unlike electromagnetic signals, which travel at the speed of light, aerosol droplets propagate at extremely slow speeds, with a lag of seconds, necessitating special design consideration. Numerous problems that could impact the proposed system must be fixed before it is put into use.

VI. ANUMERICAL RESULTS

A numerical analysis of the proposed system performance is conducted in this section by looking at the spatial temporal viral concentration and the missed detection probability. As shown in Figure 6, the receiver is a sphere with radius r_d that is parallel to the source and downwind in the y-z plane at a distance of d_x. Its centre is at $\mathbf{u_s} = [d_x, 0, H]$. All future numerical results are based on this assumption. The receiver is also assumed to be located in a fully sterile environment. In the numerical results that follow, we use the settings listed in Table I unless otherwise specified.

TABLE IV

Parameter	Values
$\bar{u}$	140 cm/sec
H	180 cm
K	0.242 cm²/sec
r_d	2 cm

In the first numerical scenario, we investigate the effect of distance and airflow velocity on the received virus concentration at the receiver side. Assuming a sampling interval of 3 seconds, we examine the obtained viral concentration performance as a ratio of the released virus r versus the distance between the infected person and the receiver for different u ranges. With velocities less than 140 cm/s, the air flow velocities are chosen to mimic coughing, artificial air flow, and exhaled nasal breaths. First, we see that the main factor influencing the spatial viral signature is airflow velocity. Raising u may cause the concentration to drop according to the mass conservation equation, but it may also expand the detection area [53]. As a result, employing air flow aids in expanding the spatial coverage of the detection, but it may also reduce the concentration below a detectable level.

VII. CONCLUSION

The discovery created a new field of research in MC: the detection, spread, and transmission of viral aerosols. Viral detection may benefit from an understanding of the kinetics of virus transmission through mathematical modelling of the aerosol channel. The use of artificial airflow is a key enabler for the viral detection system, as it allows the identification of viruses and overcomes the slowness of diffusion-based propagation. The simulation findings show that several parameters affect missed detection, such as air velocity, distance, virus flow rate, and receiver binding efficiency. The proposed mathematical problem was studied using the steady state analysis of virus transmission and detection due to breathing. The system's response to coughs and sneezes, as well as transient analysis, were added. The transient analysis affects several aspects of receiver design, such as memory channel behaviour and synchronization. By adding complex wind fields and lowering the assumptions, the work can be extended in subsequent research to provide diverse turbulence behaviour. Researching different sources, interference, and turbulence models is also crucial, as is optimizing the receivers' size and/or location. Finally, this research could be extended to anticipating pandemics and implementing precautionary measures.

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