

Applying Intelligent Reflector Surfaces for Detecting Respiratory Aerosol Cloud using Terahertz Signals

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Abstract—The recent COVID-19 pandemic has driven researchers from different spectrum to develop novel solutions that can improve detection and understanding of SARS-CoV-2 virus. In this article we propose the use of Intelligent Reflector Surface (IRS) emitting terahertz signals to detect airborne respiratory aerosol cloud that are secreted from people. Our proposed approach makes use of future IRS infrastructure to extend beyond communication functionality by adding environmental scanning for aerosol clouds. Simulations have also been conducted to analyze the accuracy of aerosol cloud detection based on a signal scanning and path optimization algorithm. Utilizing IRS for detecting respiratory aerosol cloud can lead to new added value of telecommunication infrastructures for sensor monitoring data that can be used for public health.

Index Terms—COVID-19, Intelligent Reflector Surface, 6G, Public Health.

I. INTRODUCTION

IN the fight against the COVID-19 pandemic, various disciplines have come together to develop solutions that will help in not only eradicating the virus, but also characterizing its propagation properties to curb the pandemic. The ICT research community has also contributed to this effort, and this includes developing new contact tracing tools as well as the use of AI to assist in mass surveillance systems [1]. Having knowledge of whom an infected individual may have exposed to SARS-CoV-2 allows health agencies to selectively quarantine people at risk and halt the further spread of viral infection. This paper joins this global effort by using 6G wireless network infrastructure to detect sources of viral outbreaks that can help curb pandemic spreading. Expiratory activities such as coughing and sneezing generate vast amounts of aerosols and large droplets. Recent studies have shown that the dominant way of SARS-CoV-2 are the aerosol transmissions [2].

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We present a solution using 6G wireless signals to detect these high propulsion respiratory clouds (e.g., sneezing) which, in case of an airborne virus infection significantly increase the viral particle concentration in the air. This information can be utilized by public health officials to understand the spreading pattern of an infection, provide guidance for ventilation, or improve contact tracing accuracy. Our strategy exploits the current 6G research trends in utilizing *Terahertz* frequency spectrum for sensing, and in particular this spectrum's unique molecular absorption properties. Given the sensitivity of the terahertz spectrum that requires Line-of-Sight (LoS), the research community has proposed a new infrastructure called *Intelligent Reflector Surfaces (IRS)* that will bounce and intelligently re-direct signals from the walls, allowing a degree of control over the wireless propagation environment. These consist of metasurfaces integrated and controlled with programmable electronics and allow for total control over the direction, polarization, amplitude, and phase of impinging waves [3]. This means that an indoor environment can be covered by intersecting wireless thin beam rays (as shown in Figure 1), providing an opportunity to track and localize respiratory vapor cloud by monitoring spatial signal attenuation that are reflected from IRS. In this paper we demonstrate how scanning of indoor areas using terahertz signals and IRS can be seamlessly integrated with their main role for wireless communications, but also for detection of respiratory aerosol clouds. Through a simulation campaign we demonstrate the reliability of such a system in respiratory vapor detection, and we discuss the challenges, future directions, and effects this approach would have on future communication systems.

II. AIRBORNE VIRAL PROPAGATION

The COVID-19 has predominantly spread between people through a number of mechanisms. The previous sole belief was that the virus was spreading through viral droplets that will drop to surfaces. This largely is based on individuals who have the virus and will disperse them through high-propulsion respiratory clouds, such as coughing or sneezing. In particular, the case of sneezing can expel a large quantity of virus through the jet force that exits from the nose and mouth, propelling them through a long distance. However,

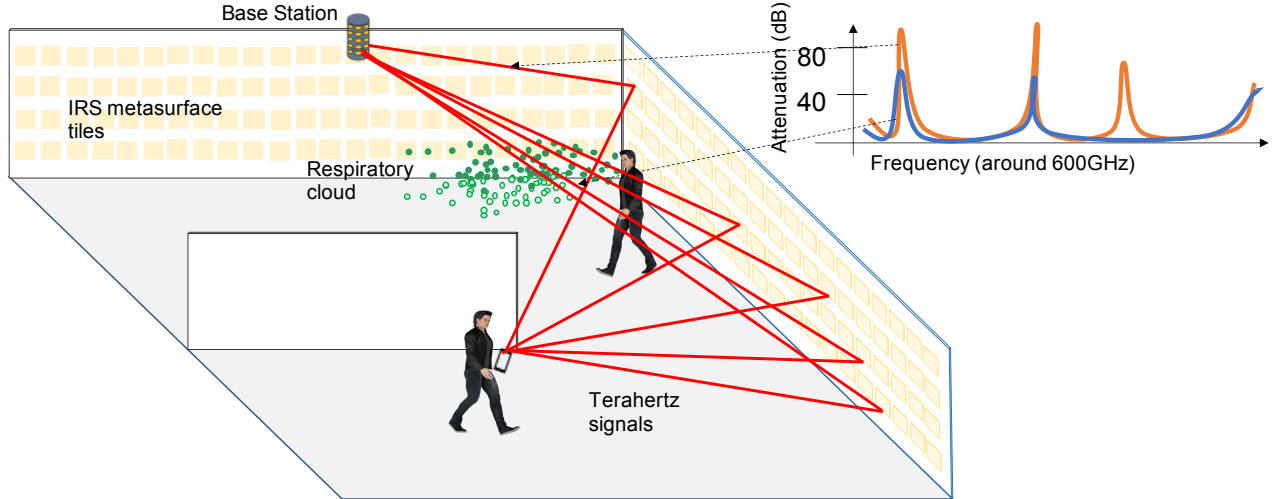


Fig. 1. The signals that are reflected from the IRS can criss-cross specific regions of respiratory cloud, where its attenuation is used to determine the location and spreading patterns of the airborne droplets. As shown in this figure, this is based on the terahertz signals that have high molecular absorption factor that leads to signal attenuation.

a recent study found that the virus can also be transmitted through airborne transmission [2]. In the works by Li et al. [4], air flow simulation was conducted to determine how the viral droplets will propagate under different conditions. The study found that the propagation is highly impacted by the evaporation levels within the air. This is also dependent on the size of the droplets, where usually sizes are approximately 8 - 16 μm , but the highest viral propagation exists for droplets that are of the size of 32 - 40 μm . In the case where there is no evaporation, the propagation of the clouds can be for a few meters at high density where the airborne viral particles can sit in the air for up to 10 seconds. However, this can lead to airborne transmission for environments with low humidity conditions. Research studies have also been conducted in understanding how virus propagate through the air using molecular communications theory [5]. In [6], a thorough analysis was conducted on molecular communication models and data for viral propagation, and in particular for breathing as well as high-propulsion jet emission through coughing and sneezing.

III. TERAHERTZ SIGNALS AND INTELLIGENT SURFACE REFLECTORS

A. Terahertz Signals Properties

Terahertz electromagnetic waves suffer from high free space path loss and molecular absorption losses, creating a requirement for near LoS communication [7]. The most significant and severe absorption losses are due to water vapor [8]. Instead of looking at the molecular absorption properties of terahertz waves as a negative, our approach exploits this signal attenuation as a tool for aerosol cloud detection.

The attenuation plot in Figure 1 illustrates the effect of temperature and humidity on molecular absorption loss of electromagnetic waves at frequencies of our interest. The resonance pattern for water vapor in the terahertz spectrum

produces windows where the absorption coefficients are small, and windows where the absorption coefficients are large, i.e., the channel is frequency selective. There is a stark difference in attenuation a wave traveling through a respiratory cloud suffers in comparison to a wave propagation through standard room conditions.

By transmitting a signal through a region of space and measuring the received signal power at the receiver as illustrated in Figure 1, our aim is to deduce whether that signal has passed through an increased water vapor concentration. Using the beam-forming and reflection capabilities of the IRS, the multiple thin beam rays can be used to scan all areas of an indoor environment looking for a sudden increase in respiratory cloud vapor concentration as illustrated in Figure 1. This respiratory vapor cloud can then be tracked as it evolves over time, and user devices can be informed of its location. Using the received power measurement to detect the presence of a respiratory vapor cloud, requires no alternation of the information-bearing signal and the communication protocol in place. The service would piggyback on normal wireless communications.

B. Intelligent Reflector Surfaces

IRS is a technology that exploits the different dielectric properties of materials to reflect electromagnetic waves to enhance the performance of indoor wireless communications systems by countering the higher path and molecular absorption losses of THz signals [9]–[12]. The walls in a typical office room can be covered by reflective materials that can intelligently control the properties of a THz signal (e.g., amplitude and phase) to ensure that all users have access to efficient and high data rate wireless communications links. Therefore, most of the IRS solutions proposed to date focus on this challenge, resulting in indoor Multiple Input Multiple Output (MIMO) wireless communications systems.

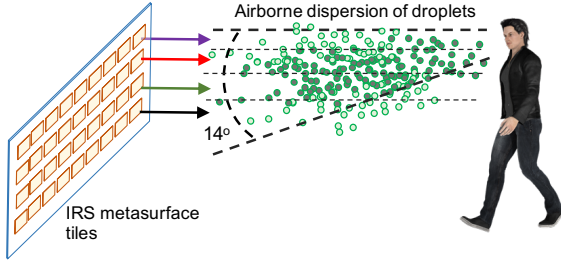


Fig. 2. The dispersion of droplets through the air can take between $1 - 14^\circ$ in environments with no evaporation (after an initial expulsion of 27.5°) [4].

A wide variety of reflective materials (i.e., metamaterial) have been utilized as the main component for the fabrication of IRS. For example, Bi et al. [13] have proposed the use of flexible ceramic microspheres that can reflect up to 95% of the incident electromagnetic wave, with a bandwidth of 0.15 THz, and obtaining resonance from 0.3 – 1.4 THz depending on their physical configuration. In a different approach, Temmar et al. [11] have selected graphene as the IRS fabricating metamaterial, achieving a high gain (≥ 8.6 dB) for 0.6 – 0.64 THz frequency range and a channel capacity of 29.10 bits/Hz for a (2×2) MIMO configuration.

IV. SCANNING FOR THE RESPIRATORY CLOUD

An important question for our approach is *"How to efficiently check a room for the presence of respiratory cloud using a THz transmitter and a group of IRS on the room walls?"* We start by digitising the room layout and dividing it into a grid, creating a pixelated image of the room. The field-of-view of an IRS depends on the geometry of its construction and, therefore, it is not guaranteed to be able to reflect an impinging signal with a full 180 degrees of freedom. This is mirrored within the simulation environment where a non-ideal field-of-view of 140 degrees is assumed. The idea of using multiple IRS in the indoor communication scenario is to avoid blockages by bouncing the signal between several IRS on its way between the base station and the user. By increasing the number of reflections in a path, signals can also take more unique and distinct trajectories around the room. Two different propagation path types will be considered which utilize differing amounts of these reflections; two and three bounces as indicated in Figure 3.

When a grid (a pixel in our discretized layout) is selected to be scanned for the presence of respiratory cloud, a limit on the amount of different signal paths to be used has to be set as it is infeasible to use all IRS in the room to scan a single grid. The best paths available are also chosen to be used. It is preferable for the rays which intersect the grid to come from significantly different trajectories, travelling through different sections of the room. These paths are chosen using the *Smart path* selection technique by first considering the unit circle around the grid to be scanned. Depending on the maximum paths chosen, the 180 degree angle around the selected grid is segmented. For example, consider a scenario where a maximum of three paths are chosen. The 180 degree

angle around the grid is split into three equal segments as if it has been cut into three equal pizza slices, each slice being 60 degrees. Within each pizza slice, a ray path is chosen that enters the grid from within that 60 degree segment. As there will be multiple IRS that have paths within each slice, the IRS and path with the shortest propagation is chosen in order to minimise path loss. This results in the selected grid being scanned from IRS evenly distributed around its unit circle, harnessing IRS from all corners of the room. Allowing a greater amount of maximum IRS increases the amount of slices/segments, and hence increases the resolution of how the grid will be intersected from multiple signal beams.

As seen in Figure 2, each row of metasurface can emit horizontal signals that will sense a particular height of the droplets. Therefore, the 2D scanning process can traverse row by row through the metasurface tiles of the IRS. For each signal path, two received powers will be calculated: a control power, and an actual received power. These two powers will be compared to each other and a binary decision made on whether a selected grid contains a respiratory cloud. First, a control received power is calculated where it is assumed that there is no respiratory cloud present in the room. For the same ray path, its received power is calculated using the actual simulation room's data. For each grid the ray passes through, an absorption coefficient for that grid is calculated using baseline temperature and relative humidity data. All the grids on the ray's path are tallied. Using this tally, the ray's total propagation distance can be divided into segments proportional to the grid conditions it has passed through. If the actual received power for each ray used to scan the grid is lower than its complement control received power, then the selected grid is classified as having a respiratory cloud present.

The described approach allows us to (1) check a particular grid for the presence of respiratory cloud, and (2) diversify the rays in space. The simulations we will present in the remainder of the paper are small enough to allow for exhaustive search, checking all grids. In larger spaces, practical considerations ask for smart, guided grid selection and path optimization process. Here, experience from uncertainty modeling, mapping, or image processing, with associated tools such as Markov random fields can be helpful. Knowledge about grid's neighbours affects the expectation of the respiratory cloud in a particular grid, and the grids with higher expectation can be prioritised. Alongside this probabilistic approach, we use grid trail elimination as well, where if a given ray's received power matches the expected power, grids along the ray are marked as currently unaffected by the respiratory cloud. This reduces the search space for grids that need scanning.

V. SIMULATIONS

A. Simulator Development

We constructed a 2D indoor simulation environment scenario of room size 10 m by 10 m. The room was split into grids of size 10 cm by 10 cm. Every grid element holds information on that specific area of the room including its temperature, humidity, and water vapor concentration, i.e., the amount of water molecules present.

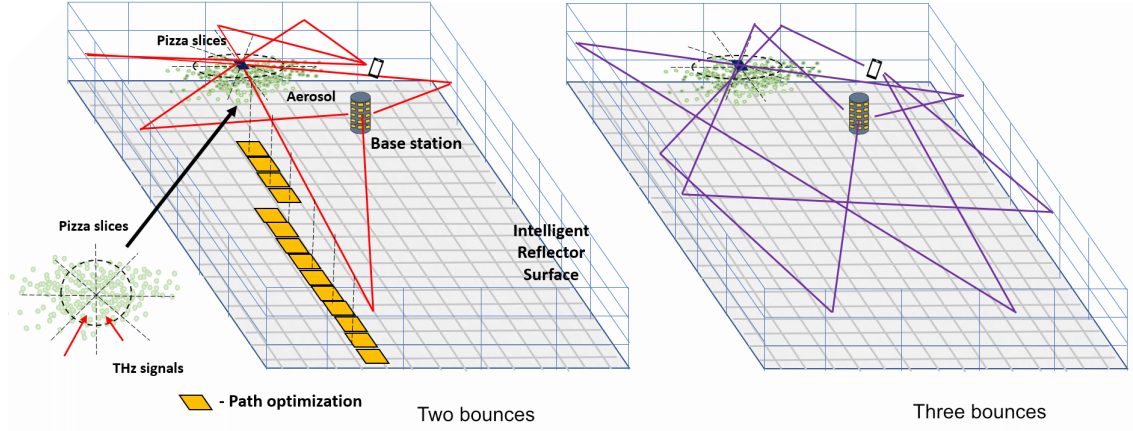


Fig. 3. Representation of the different propagation paths employed to scan the grid in the centre of the respiratory cloud (two bounces, i.e. ray consisting of three line segments, and three bounces, consisting of four line segments). Diverse paths produced by pizza slice approach are shown, alongside the intuition for path optimization.

A base station is added to the centre grid of the room, and acts as the transmitter for all signals. A network user's position can be specified as an input, and its location placed in the respective grid to act as the signal receiver. The IRS are placed on the walls of the room via these grids. The IRS locations and total coverage on the walls can, therefore, be varied when initialising the grids and the simulation environment. Respiratory clouds are modeled by adjusting the water molecule concentration, temperature, and humidity in these grids. Using these properties we simulate the respiratory cloud propagation (using the algorithm proposed by [14]) considering its physical properties, such as air (environment and the fraction that leave the person's mouth) and droplets densities, as well as the air viscosity. Through this method, we also determine the number of droplets in the cloud and its temporal dynamics that influences the detection of the respiratory cloud by our proposed technique.

Using this simulation environment and the propagation loss model, ray-tracing methods were used to model the straight line propagation paths of transmitted terahertz signals and record the received signal power, considering free space pathloss. The scanning algorithm was designed to allow any particular location, i.e. a grid, in the room to be scanned for the presence of a respiratory cloud. When a grid is chosen to be scanned, the ray propagation paths are formulated from the base station to the user device which passes through the grid. The idea is to be able to have a selection of multiple possible ray paths, from the base station, reflected from the IRS, which arrive at the end user. These ray paths must crisscross or intersect the selected grid to be scanned. A number of these paths can then be chosen and signals transmitted along them.

The performance of the scanning algorithms in detecting the presence of a respiratory cloud was measured using binary classification metrics. This consists of *precision*, which is the probability that a grid that is classified as having a respiratory cloud actually has a respiratory cloud present, and *accuracy*, which is the probability that a classification produced by the scanning algorithms is correct.

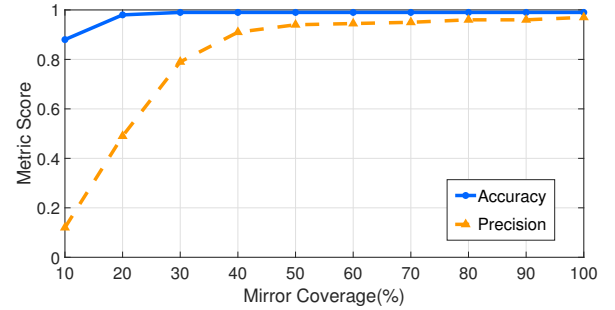


Fig. 4. Metric scores versus IRS coverage on the walls of the indoor room.

The effect of varying the following parameters on the performance of the scanning algorithm was examined: (1) the percentage IRS coverage of the walls of the indoor room, (2) the type and amount of signal path used to scan a single grid, and (3) the effect of user and respiratory cloud location. Operating frequency of 0.6 THz was used based on a recent work in [15], which demonstrated terahertz signal of 666 GHz achieving a peak data-rate of 9.5 Gbps at a distance of 590 meters.

B. Results

1) *IRS Coverage*: Experiments were conducted with a varying percentage of wall area covered by the IRS. Scanning simulations were executed for percentage IRS cover from 10% to 100%. For every grid, a maximum of 10 ray paths were chosen to scan that grid, with a maximum of 5 of both propagation path types (two bounces versus three bounces). As suggested earlier, there is no added benefit in significantly increasing the number of rays probing a grid.

The results presented in Figure 4 indicate that an exhaustive deployment of IRS in an indoor room is not needed in order for the scanning system to perform well. In fact, the scanning system performs nearly just as well with 50% coverage as with 100%. This reduces a hardware barrier to implementing such

a scanning system, as it can still function in an environment with a limited number of IRS. Below 30% coverage, the performance of the scanning algorithm exponentially decreases.

2) *Signal Paths*: Experimental results are presented in Figure 5 which uncover the optimal number of rays needed to scan a single grid. This set of experimental results also compares the performance of each path type, with varying allowable numbers of ray paths per scanned grid. Averages from experimental iterations over percentage IRS coverage of 100%, 50%, and 30% were calculated, and the entire room was scanned.

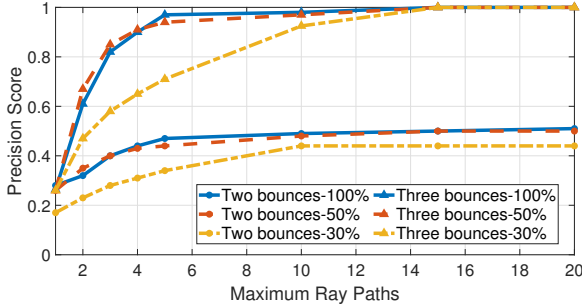


Fig. 5. Precision score versus maximum number of two-bounce or three-bounce ray paths per scanned grid. Results are presented for an IRS coverage of 100%, 50%, and 30%.

As one would expect, at lower IRS coverage and lower number of maximum rays per grid scan, the performance of the scanning algorithm decreases. Interestingly, at a IRS coverage of 30% the performance drops significantly below 10 maximum rays per grid scan. However, at an IRS coverage of 50% and 100% the performance remains relatively stable until the maximum rays per grid drops below 5. This would indicate that having a higher percentage IRS coverage in an indoor room would allow for less ray paths to be used when scanning the room. Having a larger pool of IRS in the room allows for a better selection of ray paths, and hence better performance with less rays. However, having greater IRS coverage in a room presents a problem with their construction costs and the physical and monetary barrier to installing them. Not every material can be installed with an IRS, e.g. glass windows. On the other hand, using more ray paths when scanning will require more signals to be transmitted from the base station. This would lead to higher power consumption costs when operating the scanning service. While three-bounce paths outperform two-bounce paths, it must be highlighted that three-bounce paths have a longer propagation distance and will hence suffer higher path losses. In order to utilize three-bounce paths, antenna gain must be adequate to combat these larger losses.

3) *User and Respiratory Cloud Location*: The effect of both the user and respiratory cloud location on the performance of the scanning is presented. Two different cloud locations were considered and are displayed in Figure 6. The first cloud location lies to the diagonal of the base station. The second cloud location is above the base station, along its y axis. The locations were only considered in one quadrant of the room, as the results in one quadrant would mirror those

gathered in the three others. A respiratory cloud, therefore, will lie either to the diagonal of the base station, along its x or y axis, or somewhere in between these two cases. Performing experiments on these two main cases will uncover the challenges faced by the scanning algorithm for changeable respiratory cloud location.

At each of the two respiratory cloud locations, simulations were executed for eight different permutations of user location. The user locations denoted 1 through 8 in Figure 6 lie at a distance of 1m around the respiratory cloud. From the spider charts the scanning algorithm can be seen to slightly underperform for the second cloud position but not significantly. This is due to the second cloud location being closer to the base station, effectively cutting off the base station's field-of-view with no respiratory cloud. The closer the respiratory cloud is to the base station, the greater the probability is for a scanning ray to pass through the cloud, irrespective of the specific grid that is being scanned. This suggests that the position of the base station in the indoor scenario impacts significantly on the performance of the scanning algorithms.

There is one user location which results in a significant performance drop for both cloud locations when two-bounce paths are used by the scanning algorithm, and this is when the user is located in-between the respiratory cloud and the base station. The three-bounce paths do not suffer from such a performance drop as they do not face the issue of colinearity of rays in this configuration.

VI. CHALLENGES AND FUTURE DIRECTIONS

The development of respiratory aerosol cloud tracking based on the terahertz spectrum needs more development and analysis despite the promising concept and results shown in this paper. Below we list and discuss some of these challenges, and potential future directions of this technology for integration with the envisioned 6G infrastructure and new types of services for telecoms infrastructures.

A. Moving Indoor Objects

As discussed in this paper, respiratory aerosol clouds dissipate over the air as their droplets diffuse based on random motion towards other indoor areas, surfaces and floors. However, the dissipation of the respiratory aerosol cloud depends also on the airflow present indoors, as jet streams and turbulent sources will affect how the respiratory aerosol cloud dissipates. Jet streams can move the respiratory aerosol cloud faster to other areas depending on its source, potentially removing the respiratory aerosol cloud from the indoor space altogether. Turbulent sources from moving people and objects will also interfere with respiratory aerosol cloud dissipation, either abruptly dislocating it and breaking the respiratory aerosol cloud into multiple smaller ones. Since we consider the static dissipation of clouds, it is unclear how cloud scanning techniques can cope with the airflow effects on the respiratory aerosol cloud. This requires a deep characterization of the sources of jet streams and turbulences and the system response on those, as airflow properties such as velocity and movement patterns need to be coupled with existing models

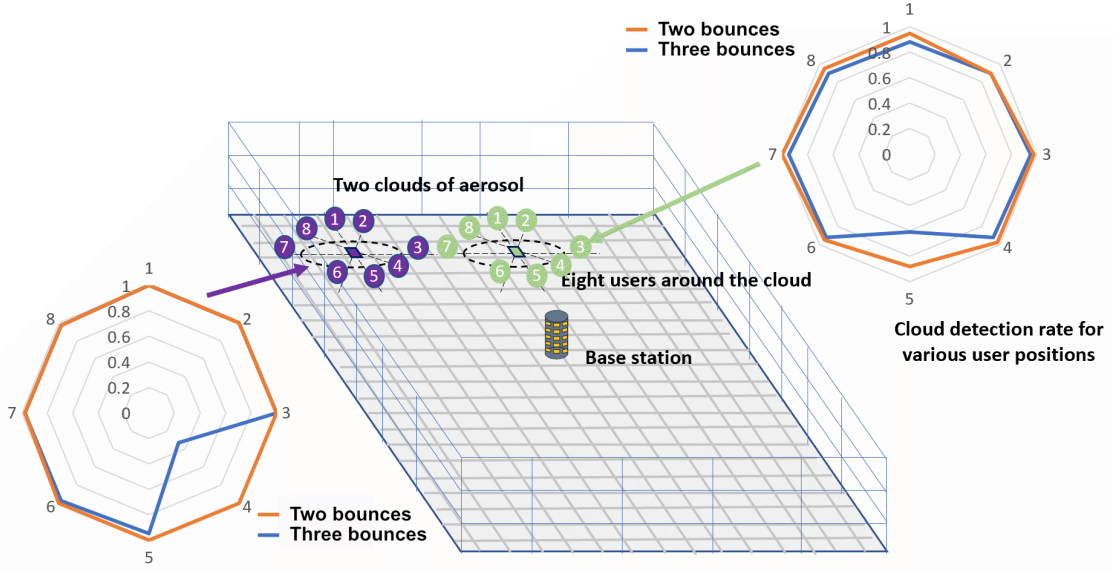


Fig. 6. Two characteristic options for respiratory cloud position (diagonal and orthogonal), with 8 different positions of users around them. The spider charts correspond to the precision of detection w.r.t. user position around the cloud.

in respiratory aerosol cloud dissipation. Even though there is existing literature on this topic, the need is for actual studies on the patterns of jet streams and turbulences indoors with the accuracy of the cloud tracking system and what adaptation is needed to cope with scaling airflow effects.

B. Environment Effects on Multiple Ray Scanning Techniques

Since the propagation of terahertz beams depends on the air content in a given indoor scenario, the environmental factors that affect signal transmission will also impact the multiple ray scanning method used to track respiratory aerosol clouds. Besides the airflow effects already discussed in the previous section, humidity is a leading factor in terahertz signal degradation that will cause poor signal propagation at certain levels. The depth of the room's scanning technique depends on high-quality signals that will pass through respiratory aerosol clouds to be detected. High humidity levels mean that the signal will be degraded so much that the respiratory aerosol cloud will disintegrate quickly. Currently, the research community is focused on solving signal degradation issues based on humidity. However, since our proposed approach aims to track respiratory aerosol cloud progression in the room, the degrees of freedom are higher for this scenario when designing solutions. For example, since we are not focused on maintaining a required level of data rate, this can result in other methods that focuses on respiratory aerosol cloud tracking even with high humidity levels.

C. Increased OPEX AND CAPEX Costs

The efficiency of the sensing should determine the impact on the OPEX and CAPEX of the wireless network infrastructure. When scaling up the room's dimension, sensing will largely depend on the constant Thz signal radiation in multiple locations so that the signal strength is enough to reach a

meaningful recording of the respiratory aerosol cloud. Sensing efficiency also depends on the number of reflections points on walls. Compared to the planned infrastructure for 6G, there are no added CAPEX costs since the integration of terahertz base stations and IRS are at ongoing development for 6G. However, in terms of OPEX, energy consumption may increase based on the level of continuous sensing that is performed. It will be interesting to know how much energy is increased and what techniques can be developed to provide continuous monitoring without increasing the energy consumption.

D. New Telecoms Services

The most significant advantage of the proposed solution is the ability to use the wireless infrastructures for sensing purpose. This proposal will not rely on novel sensing hardware but will make use of the already available infrastructure. Sensing thus becomes an added commodity, whereby sensing not only respiratory aerosol clouds but other airborne agents become available. Gases and chemicals in high concentrations can also interact with the terahertz signals so that multiple agents can also be sensed. Future telecom providers can offer new services with this sensing data. For example, mobile users that are located close to polluted or toxic areas can receive data relevant to specific gases that they are exposed to and what levels. The inclusion of this service and the impact on telecom providers to offer sensed data that impacts on health can lead to new immeasurable benefits for society.

VII. CONCLUSION

The role future networks will play in maintaining public health will become increasingly pertinent in the coming decades. Experiences from the COVID-19 pandemic are emphasizing the need for a coordinated response and pervasive sensing of reliable information. Our vision of using IRS and

terahertz communications in 6G for detection and tracking of respiratory clouds recognises the unused potential of high-frequency communication systems for not only transmitting high speed data, but also for a new form of sensing that will help public health.

Future telecommunication system design need not only be motivated by conventional drivers such as achieving higher data rates and bandwidth. An expansive and ambitious vision of 6G networks is championed, whereby its success is measured by the human-centric services it can provide to its users. The respiratory cloud detection service presented shows that with the right design vision 6G networks can be more than just a tool to exchange information, and instead can become intelligent entities that actively participate in enriching and safeguarding peoples' lives.

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