On the Potential for Viruses as Nano Microwave Transmitters


Document Version:
Peer reviewed version

Queen's University Belfast - Research Portal:
Link to publication record in Queen's University Belfast Research Portal

Publisher rights
© 2021 EUMW.
This work is made available online in accordance with the publisher's policies. Please refer to any applicable terms of use of the publisher.

General rights
Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact openaccess@qub.ac.uk.

Open Access
This research has been made openly available by Queen's academics and its Open Research team. We would love to hear how access to this research benefits you. – Share your feedback with us: http://go.qub.ac.uk/oa-feedback
On the Potential for Viruses as Nano Microwave Transmitters

Gabriel G. Machado*1, Vincent F. Fusco*1
*1Centre for Wireless Innovation (CWI), Institute of Electronics, Communications and Information Technology (ECIT), School of Electronics, Electrical Engineering and Computer Science (EEECS), Queen’s University Belfast, UK
1g.machado@qub.ac.uk, 1v.fusco@ecit.qub.ac.uk

Abstract — In this paper, we report the potential use of airborne viruses as nano transmitters of mechanical and microwave signatures. Specifically, we treat the virion (virus particle) as a thin core-shell spherical structure with mechanical and electrical properties assigned and use Comsol Multiphysics to determine the mechanical natural modes of vibration. We then approximate how these may be used for the purpose of generating electromagnetic radiation, effectively making the virion behave as nano radio transmitter in the microwave band.

Keywords — Nano core-shell particles, virus, scattering, mechanical to electromagnetic conversion.

I. INTRODUCTION

According to the World Health Organisation around 650,000 people die of seasonal flu each year, while over 3,934,252 deaths related to the virus Sars-Cov-2 have been reported to July 2021 [1]. Any new approaches that could lead to rapid and reliable indication of the presence of viruses while airborne would be an immensely useful tool that would be of significant societal and economic benefit.

A virus [2] is a very small, non-cellular parasite of cells. Its genome which is composed of either DNA or RNA is enclosed in a protein coat known as a capsid, see Fig. 1a. Virions are organic nano-structures varying in size in the range 50 – 400 nm which can, depending on the virus type, be of different shapes, such as cylindrical and spherical. In the case of Covid-19 the virus has an enveloped structure consisting of a positively charged external lipid membrane shell which encloses a negatively charged capsid core containing the nucleic acids used by the virus to reproduce itself inside a living cell.

In effect the virion can be considered, to an approximation, as a pliable spherical capacitor, Fig.1b. Due to the physical construction of the virions they will exhibit natural mechanical vibration modes. This in turn will cause relative displacement of the electronic charges associated with the virion at their mechanical vibration rate, potentially leading to the virion emitting an electromagnetic (EM) signature in the frequency range determined by its mechanical vibration rate.

This paper is aimed at approximately establishing the physical limitations of the viability of using airborne enveloped viruses as nano-microwave radio transmitters emitting an electromagnetic signature that potentially could be used to indicate their presence for the purpose of detection.
III. EM SCATTERING PROPERTIES OF VIRION

A. Core-shell to homogeneous sphere approximation

To simplify our study, both electromagnetic and mechanical simulations were performed as a single homogeneous sphere. The studies found in our bibliographic review, e.g. [4], [8]–[10], show that the mechanical properties of quasi-spherical virions, such as the Young modulus ($Y_m$) and Poisson ratio are given for a homogeneous approximation and will be discussed in the next section.

For the electromagnetic approximation, we use the permittivity homogenization formulation for core-shell structures shown in (1) [11] to determine the effective permittivity $\epsilon_{eff}$, given the radius and permittivity of the shell and the core, $a$, $b$, $\epsilon_s$ and $\epsilon_c$, respectively. Here we fixed $a = 50$ nm and $a - b = 3.1$ nm, where $a$ is also the radius for the new ‘homogeneous’ particle [3], and the thickness of the shell $a - b$ is obtained from [9].

In our analysis, Comsol multiphysics [12] was used to calculate the approximate value of the enclosed charge of the nanoparticle by direct use of Gauss’s law as shown in (2). That will later be used to compute the EM power that can be transmitted due to mechanical vibrations induced by the virion. Fig. 2 illustrates the model used in Comsol to obtain $\epsilon_{eff}$ and the enclosed charge in the area of the virion which suffers the greatest displacement. The charge simulation was performed using Comsol’s Electrostatics Module, given that $a << \lambda$, where $\lambda$ is the wavelength which in this study was always $\geq 6.3$ nm. The particle was subject to an electric field (top to bottom) oscillating at 42.376 GHz, our main frequency of interest, the choice of which will be discussed in the next sections, and the charge was calculated using (2)

$$\epsilon_{eff} = \epsilon_s \frac{a^3(\epsilon_c + 2\epsilon_s) + 2b^3(\epsilon_c - \epsilon_s)}{a^3(\epsilon_c + 2\epsilon_s) - b^3(\epsilon_c - \epsilon_s)},$$

$$q = \iint_{\partial\Omega} \mathbf{D} \cdot d\mathbf{S},$$

where $\Omega$ is the surface described in the cross-section shown in Fig. 2.

For $\epsilon_c$, we treat the core as a homogeneous diisopropylamine protein solution [13], and for simplification, given the ranges of frequencies used in this paper, we use a dielectric constant of 3.04 [14], [15]. The shell dielectric constant, $\epsilon_s$ is based on the work from Hoff [16], and ranges between 2 – 27. Figure 3 plots both the range of effective permittivity which are going to be used for the calculations for the reminder of this work, and the calculated enclosed charge as a function of the shell’s dielectric constant.

B. Rayleigh scattering analysis

To an approximation we assume, following [3], that the virion is a homogeneous nanoparticle of fixed radius $a = 50$ nm and permittivity $\epsilon_{eff}$. As we will demonstrate, the dielectric constant has a significant impact in the scattered power, and therefore, in our analysis $\epsilon_{eff}$ is the mixed permittivity for the shell and core materials as previously demonstrated. If an electric field of amplitude $E_0$ impinges on the virion’s surface, the scattered power is given after the Rayleigh scattering equation [17] by (3)

$$P_s = \frac{4\pi}{3\eta_0} k^4 u_0^2 \left( \frac{\epsilon_{eff} - \epsilon_0}{\epsilon_{eff} + 2\epsilon_0} \right)^2 |E_0|^2.$$

As seen in (3), the wavelength ($k = 2\pi/\lambda$), radius, permittivity and magnitude of the incident electric field must be known for calculation of scattered power.

To calculate the permissible value of $E_0$ in air, the IEEE Std C95.1(2019) [18] defines the maximum value of incident
power density for which it is safe for humans in unrestricted free space environments. Here it is defined that for frequencies between 6 GHz to 300 GHz, the maximum power density (W/m²) is given by (4), where \( f_g \) is the frequency in GHz.

\[
P_{\text{max}} = 55 f_g^{-0.177}.
\]

To calculate \( E_i \), we can take the Pointing vector and manipulate \( S = |E_i|^2 \eta_0 \) to obtain (5)

\[
E_{\text{max}} = \sqrt{55 f_g^{-0.177}(2)\eta_0}.
\]

In order to identify possible microwave frequencies with which to excite the virion, and therefore create a mechanical vibration, mechanical eigenfrequency studies were performed in Comsol in search for its first acoustic mode of vibration. Once again, the core-shell model is simplified to a homogeneous sphere matching its mechanical properties to values found in the literature. Typical mechanical parameters of a quasi-spherical virion are, \( Y_m \) varies between 0.5 — 1.8 GPa, the density 21.275 kg/m³ (average for Sars-Cov-2) and the Poisson ratio for virus mechanics is considered to be in the order of 0.3 [8]. The resulting mechanical eigenfrequencies (varying \( Y_m \) in 0.1 GPa steps) are given in Figure 4 which plots the calculated scattered power using (3) versus the previous obtained values of \( \epsilon_{\text{eff}} \). Note that the mechanical eigenfrequencies do not depend on the value of relative permittivity.

For the EM detection of airborne nanoparticles, the thermal noise threshold (TN), given by (6), needs to be lower than the total power scattered by the virus in aerosol.

\[
\text{TN}_{\text{dBm}} = 10 \log_{10} \left( \frac{K(BW)T}{10^{-3}} \right),
\]

where \( K \) is Boltzmann constant, BW is the intermediate frequency (IF) bandwidth in Hz and \( T \) the temperature in Kelvins. For BW = 1 Hz and \( T = 293 \) K, TN = -174 dBm.

As observed in Figure 4, the scattered power increases with \( \epsilon_{\text{eff}} \) for each value of \( Y_m \), i.e different eigenfrequencies. To demonstrate how the permittivity may impact the potential for airborne virus detection, we can calculate the necessary amount of virions needed to to scatter enough power to overcome the minimum detectable signal (MDS, TN +3 dB) for an IF bandwidth of 1 Hz. The results are depicted in Fig. 5 for 4 different values of \( \epsilon_{\text{eff}} \) (for brevity). This assumes that the separation between each virion is small enough so that the phase difference is negligible at the EM frequencies used to excite the particles.

This result suggests that the number of virions required, assuming the best case scenario that the scattering from these virion nanoparticles radiate in phase, needs to be greater than \( 3.3 \times 10^9 \). For comparison, from a single cough, one person infected with a high viral load in the respiratory track may generate \( \approx 10^9 \) copies of viruses whilst a normal subject expels \( \approx 400 \) [19].

C. Enveloped virion as nano-transmitter

Using Comsol structural mechanics eigenmode module for the same homogeneous nanoparticle (with \( Y_m = 1.4 \) GPa as a typical value) as above in order to gain an understanding of the charge displacement such a particle might experience due to mechanical displacement. Here we choose to study an eigenfrequency of 42.376 GHz as this represents the mode with the greatest displacement about the \( z \) axis, see Figure 6.

We now make an approximate estimate of the radiated power generated by the accelerated charges on the virion
particle when subjected to this mode of vibration by using Larmor’s Formula, (7):

\[ P_{rad} = \frac{q^2 a^2}{6\pi \epsilon_0 c^3}. \]  

(7)

Here \( q \) is the previously calculated charge, \( a \) is the acceleration, and \( c \) is the speed of light. Considering that the chosen virion nanoparticle is vibrating in its natural frequency with the characteristics of simple harmonic motion, the acceleration can be obtained from Comsol using a local point evaluation where the displacement is greatest, which results in \( 5.23 \times 10^{14} \text{ m/s}^2 \). The displacement \( (x) \) can also be calculated by \( a = \omega^2 x \), where \( \omega = 2\pi \times 42.376 \times 10^9 \text{ rad/s} \) is the angular frequency, which results in \( x = 7.5 \text{ nm} \). We now calculate the required number of virions to achieve the MDS for \( \epsilon_{eff} = [3, 6] \) and the IF bandwidth = [1 Hz, 10 kHz].

Based on the thermal noise limit as a figure of merit, this calculation shows that, for the highest value of \( \epsilon_{eff} = 6 \), approximately 380 oscillating particles are required to achieve the MDS for an IF bandwidth of 1 Hz, increasing to \( 38 \times 10^5 \) for 10 kHz bandwidth, in contrast to \( > 3 \times 10^9 \) previously calculated based on Rayleigh scattering with the MDS for 1 Hz BW, and \( > 3 \times 10^{12} \) for MDS @ 10 kHz. Furthermore, if the lowest value of \( \epsilon_{eff} (3) \) is considered, the required number of radiating virions is 2.4 times smaller than those calculated in the previous sentence. This suggests that it might be easier to detect airborne nanoparticles (virions) by managing to mechanically vibrate them and then reading their radiated power (through EM-mechanical-EM coupling), rather than to try to directly detect their scattered signature.

IV. CONCLUSION

This work evaluated the potential use of direct EM-Mechanical-EM coupling to effectively turn virion particles into nano-transmitters. We showed that homogenised core-shell nano-particles with similar mechanical properties of viruses found in the literature resonate at microwave frequencies, and therefore an electromagnetic signature can potentially be generated from it. For the means of detection, we analytically demonstrated that the power scattered by a virion by means of Rayleigh requires a number of virions in the order of \( 10^{12} \), which can be hard to achieve in an open environment. However, if EM-mechanically-EM stimulated (supported by previous evidence experimentally provided by [7]), the number of virions required to potentially radiate sufficient energy to surpass the MDS is 7 orders of magnitude lower when compared to the Rayleigh scattering alone for the same receiver’s IF bandwidth.

REFERENCES


