Limitations on electromagnetic communication by vibrational resonances in biological systems

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Previous research in biology and physics speculates that high-frequency electromagnetic fields may be an unexplored method of cellular and subcellular communication. The predominant theory for generating electric fields in the cell is mechanical vibration of charged or polar biomolecules such as cell membranes or microtubules. The challenge to this theory is explaining how high-frequency vibrations would not be overdamped by surrounding biological media. As many of these suspected resonators are too large for atomistic molecular dynamics simulations, accurately modeling biological resonators remains an ongoing challenge. While many resonators have been studied and simulated, the general limitations on communication imposed by energy transfer arguments have not been considered. Starting with energy transfer expressions from coupled-mode theory, we derive expressions for the minimum quality factor (Q factor) required to sustain communication for both near- and far-field interactions. We compare previous simulation studies and our theory. We determine the flexing mode of microtubules as an identified resonance in the literature which meets our criteria. Our results suggest the major obstacle to meeting our criteria for effective electromagnetic communication is the trade-off between the Q factor and the plasma frequency: Resonators must be large enough to have a large Q factor, but small enough to resonate at frequencies greater than the plasma frequency.

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I. INTRODUCTION

The orchestration of biological activities requires a great deal of communication and coordination between and within cells. To this end, cells have been shown to communicate by various chemical, mechanical, and electrical mechanisms. Various researchers have suggested, however, that known signaling mechanisms might be insufficient to meet the needs of biological coordination and that cells might exploit some type of higher-frequency electromagnetic (EM) signaling [1,2].

The first of such theories dates back to when Gurwitsch performed a series of experiments claiming to support the theory of mitogenetic radiation. Monitoring two sets of chemically separate onion root cells, he observed an increase in mitosis if a quartz barrier separated detector roots from actively dividing roots, but no such effect if the barrier was glass. Because ultraviolet light can pass through quartz but not regular glass, he suggested the existence of cellular radiation [1]. Western researchers were unable to reproduce his results using scientific methods [3]. Several experiments have since used various electromagnetic barriers in a similar vein to Gurwitsch's studies to establish evidence of cell-to-cell communication, though these studies are mixed in their findings [1,4–6].

From a biophysical perspective, an open question is how cells would ever purposefully generate an electromagnetic field of sufficient strength such that a neighboring cell could detect it. Fröhlich theorized that collections of electrically polar proteins could exhibit coherent vibrations. His work even suggested that the vibrating structures could be condensed and display macroscopic quantum coherence, in a manner similar to Bose-Einstein condensation [7–9]. No examples of such condensates have been found and further theoretical research has concluded that such condensates are "inaccessible in a biological environment" [10].

Even without the exotic quantum properties predicted by Fröhlich, most hypotheses of cellular EM generation involve some sort of electromechanical coupling. If a cell could somehow deliver energy to charged or polar proteins and induce high-frequency mechanical vibrations, the resulting oscillation of charges would produce a time-varying field. Various structures have been investigated as potential EM receivers or transmitters, namely, the microtubules of the cytoskeleton [11–13], cell membranes [14], viruses [15–18], and DNA [19,20]. While purely electromagnetic resonances have also been investigated [21], in this work we limit ourselves to structures where an electromagnetic field couples into a mechanical mode.

Accurately modeling the many hypotheses of electromechanical signaling remains a difficult problem. Fundamentally, however, all these mechanisms can be distilled to interactions with coupled resonators and electromagnetic fields. In this work, instead of modeling specific mechanisms and evaluating their ability to sustain communication, we seek to abstractly model the problem of coupled resonator communication.

While defining "purposeful communication" in a physically meaningful way is certainly challenging, in this work we will consider an interaction significant if it imparts more energy than the background thermal energy. This is a necessary but not sufficient condition for communication to occur.

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Since most of the proposed hypotheses of biological EM communication are concerned with intra- and intercellular communication, we focus on structures with length scales ranging from the molecular to the cellular level (up to 10 μm). Larger structures such as cell aggregates and tissues will not be considered.

The quality factor (Q factor) of a resonator is a parameter that describes how strongly a resonator's oscillations are damped. We derive expressions for the minimum Q factor required for an oscillator to interact with an incoming plane wave and for interacting oscillators in each other's near field. We evaluate where past studies fit into our framework and draw conclusions about the likelihood of these structures engaging in electromagnetic communication between or within cells.

Electric-field screening in electrolytic media

An important barrier to intercellular electric-field communication is the impact of screening from counterions in biological media. Charged or polar molecules attract a counterion cloud around them, exponentially attenuating electrostatic fields after a few molecular layers. The Debye length characterizes the size of the counterion cloud and is about 1 nm for cytosol [22]. For electromagnetic interactions to be considered long distance, they must occur at length scales larger than the Debye length.

Time varying fields, however, can overcome screening from conductive media if the oscillation rate can exceed the mobility of the counterions. Because our length scales of interest are much smaller than relevant skin depths at these frequencies, we can choose to ignore skin depth effects. The conductive medium then acts as a high-pass filter with a cutoff around the Maxwell, or plasma, frequency, given by $\omega_p = \sigma/\epsilon$, where σ is the conductivity of the medium and ϵ is the permittivity [23]. This is often expressed as a complex frequency-dependent permittivity given by $\underline{\epsilon} = \epsilon - i\sigma/\omega$. Compared to fields in a lossless dielectric, fields are attenuated by a factor of A given by

$$A(\omega) = \frac{1/\underline{\epsilon}}{1/\epsilon} = \frac{\epsilon\omega}{\epsilon\omega - i\sigma} = \frac{1}{1 - i\omega_p/\omega}. \tag{1}$$

For biological solutions such as cytosol, the conductivity is approximately 1.1 S/m and the relative permittivity is about the same as water, which is approximately 80 [24]. Therefore, the Maxwell frequency is approximately 250 MHz, though this will of course vary based on the conductivity of the solution [24].

II. MINIMUM Q FACTOR FOR FAR-FIELD INTERACTIONS

First we examine the possibility of cell-to-cell communication through far-field electromagnetic waves. Instead of focusing on how the fields would be generated in the first place, we analyze the case of some resonant dipole protein being hit with an incoming plane wave as depicted in Fig. 1(a). Our analysis is similar to that of Adair in which he explored how low-power microwaves might influence biological resonators [25]. Unlike Adair, we model the system as an antenna and use the Wheeler-Chu limit to find a bound on our scattering Q factor, thus allowing us to relate the Q factor to the resonator size. We will define a minimum absorption Q factor required for any resonator to absorb significant energy (greater than the background thermal bath) from an incoming plane wave using the absorption cross section given by coupled-mode theory.

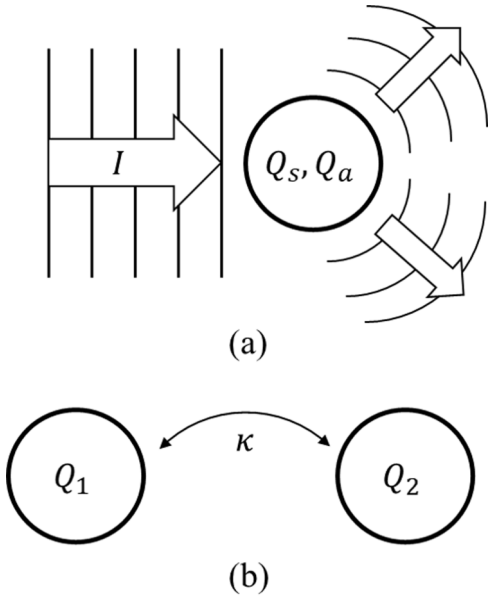

FIG. 1. Illustration of resonators interacting with electromagnetic fields. (a) Incident field with intensity I scattering off a resonator with scattering (radiative) quality factor Q_s and absorption quality factor Q_a. (b) Two resonators with their own quality factors coupled in the near field with coupling coefficient κ.

A. Energy absorbed by the resonant scatterer

We can calculate the power absorbed by the resonator in Fig. 1(a) by defining an absorption cross section. The power absorbed (P_a) by the resonator when hit with an incoming plane wave with intensity I is given by

$$P_a = \sigma_a I, \tag{2}$$

where σ_a is the absorption cross section with units of area. The absorption cross section of a resonant dipole hit with an incident electromagnetic plane wave is given by Eq. (3), which is a form of the Breit-Wigner formula and has also been proven for more general cases using coupled-mode theory [26,27]:

$$\sigma_a(\omega) = \frac{3\lambda^2}{2\pi} \frac{\Gamma_s \Gamma_a}{(\omega - \omega_0)^2 + \Gamma^2}. \tag{3}$$

Here λ is the wavelength, Γ_s is the scattering spectral half-width at half maximum (units of frequency), Γ_a is the absorption spectral half-width at half maximum, ω is the angular frequency, ω_0 is the resonant frequency, and the total width $\Gamma = \Gamma_s + \Gamma_a$. The total width is the inverse of the corresponding relaxation time of the resonator ($\Gamma = 1/\tau$). This expression is valid for electrically small (much smaller than λ) resonant dipoles near the resonant frequency.

The total Q factor is defined as the ratio of the peak energy stored in the resonator to the energy lost (absorbed) per cycle.

This can also be expressed in terms of the resonant frequency and the relaxation time of the resonator

$$Q \equiv \frac{\omega_0 U_{\max}}{P_a} = \frac{\omega_0 \tau}{2}. \tag{4}$$

The maximum energy the resonator can store is therefore

$$U_{\max} = P_a \tau/2 = \sigma_a I/2\Gamma. \tag{5}$$

The absorption cross section, and therefore the power absorbed, is largest at the resonant frequency,

$$\sigma_a(\omega_0) = \frac{3\lambda^2}{2\pi}\frac{\Gamma_s \Gamma_a}{\Gamma^2}. \tag{6}$$

The lowest anticipated frequencies of cell-to-cell communication are around 100 MHz. At lower frequencies, the electric fields are attenuated by Debye screening as discussed in Sec. I. This means that the smallest wavelength of interest in free space is approximately 3 mm (or about 340 μm in water). As mentioned previously, our length scale of interest in expected biological resonators is at most on the order of 10 μm; therefore, we can safely assume that the resonator is much smaller than the wavelength. It follows that the absorption width is much larger than the scattering width ($\Gamma_a \gg \Gamma_s$). In antenna physics terms, this is the same conclusion one would draw for an electrically small antenna. The resonant cross section can therefore be approximated as

$$\sigma_a(\omega_0) \approx \frac{3\lambda^2}{2\pi}\frac{\Gamma_s}{\Gamma_a}. \tag{7}$$

The maximum energy the resonator can store can therefore be approximated as well,

$$U_{\max}(\omega_0) = \sigma_a(\omega_0) I/2\Gamma \approx \frac{3I\lambda^2\Gamma_s}{2\pi\Gamma_a^2}. \tag{8}$$

In order for an interaction to be considered biologically significant, the resonator must be able to store more than thermal energy ($k_B T$, where k_B is the Boltzmann constant and T is temperature) from the interaction. For N resonators acting coherently, that restriction may be relaxed to $k_B T/\sqrt{N}$ [25]. By setting Eq. (8) equal to this minimum energy, we can solve for the maximum absorption width for which significant interaction could occur,

$$\Gamma_a < \sqrt{\frac{3I\lambda^2\Gamma_s\sqrt{N}}{2\pi k_B T}}. \tag{9}$$

B. Limiting the scattering width using the Wheeler-Chu limit

In order to set bounds on Eq. (9), we need to set a bound on the scattering width. From Eq. (4) we see that the resonant widths are related to Q factors by $\Gamma_i = \omega/2Q_i$. The absorption width can be shown to be related to the internal loss of the resonator (energy absorbed by the resonator) and the scattering width is related to the radiative loss of the resonator (energy reflected back into the surroundings).

By analyzing the resonator as a small antenna, we can set bounds on the Q factor based on only frequency and size. The Wheeler-Chu limit sets a lower limit on the scattering Q factor of any small antenna [28],

$$Q_s \geqslant \frac{1}{k^3 a^3}, \tag{10}$$

where $k = 2\pi/\lambda$ and a is the radius of the smallest sphere enclosing the resonator. The wavelength is given by $\lambda = c_0/f\sqrt{\epsilon_r}$, where ϵ_r is the relative permittivity of the medium and c_0 is the speed of light in a vacuum. Achieving the Wheeler-Chu limit is difficult in most small antenna designs, so it is unlikely that a biological resonator would even approach this limit.

C. Minimum absorption Q factor

First, we replace the widths in Eq. (9) with their corresponding Q factors. To assume the best case scenario, we set the scattering Q factor $Q_s = 1/k^3 a^3$ from Eq. (10). This gives us the following expression for the lower bound of the absorption Q factor required to store more than background thermal energy from an incoming plane wave:

$$Q_a \geqslant \sqrt{\frac{c_0 k_B T}{6\pi I a^3 \sqrt{\epsilon_r N}}}. \tag{11}$$

Note that Eq. (11) is dependent only on the temperature, the plane-wave intensity, the permittivity of the medium, the number of resonators, and the size of the resonator. So long as the resonator is much smaller than the wavelength, the requisite Q_a is independent of frequency.

One upper limit of the plane-wave intensity can be derived from the power generated by a single cell. From thermodynamic arguments, a single human cell generates on the order of 10^{-12} W [29]. It should be noted that, given the wide variety of cell types in biology, the actual power consumption of any given cell may deviate from this figure significantly, though we believe it to be a reasonable average. If we assume a relatively small cell with a 1-μm radius, we can estimate the maximum possible radiation intensity as $I = P/4\pi r^2$, giving us 0.08 W/m^2, or 8×10^{-3} mW/cm^2. Note that this is much smaller than the maximum intensity allowed by the FCC for general population EM exposure between 1.5 and 100 GHz, which is 1 mW/cm^2 [30].

In Fig. 2 we plot the minimum Q factor for both of these power intensities as a function of resonator size. We assume that the dielectric of the medium will be similar to water and have a relative permittivity of 80. The temperature will be assumed to be 300 K. We see that as the resonator becomes larger, the Q factor required decreases. The requisite Q factor also decreases as the power intensity increases. We also see that increasing the number of coherent resonators can decrease the minimum Q factor, though not dramatically. As suggested by Eq. (11), it requires 10 000 coherent resonators to result in a factor of 10 decrease for the minimum Q factor. The Q factors required for subcellular resonators (10–100 nm) are quite large (greater than 100) given the low-power intensity. The Q factors required for larger resonators are smaller, though maintaining many large resonators in coherence would require significant volume. This is consistent with past works which have evaluated far-field coupling of biological resonators to be insignificant at nonthermal levels [25,31,32].

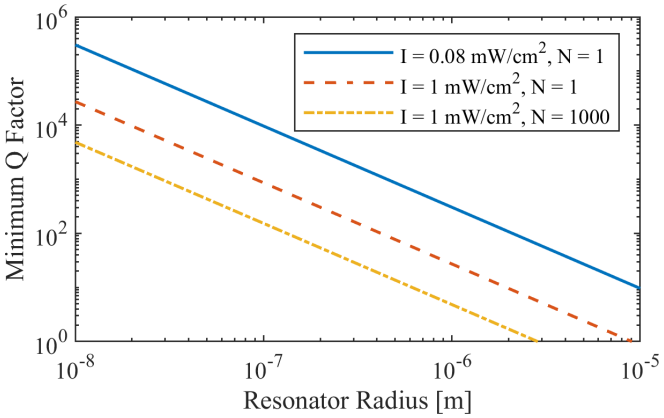

FIG. 2. Minimum Q factor required for an incoming plane wave of intensity I to impart more energy than k_BT on a dipole resonator, plotted as a function of the radius of the smallest sphere enclosing the resonator. The temperature is assumed to be 300 K and the relative permittivity of the media is 80 (water).

III. MINIMUM Q FACTOR FOR NEAR-FIELD INTERACTIONS

We can make similar arguments to construct a minimum Q factor for two resonators with a coupled near field, corresponding to the case in Fig. 1(b). Energy transfer between coupled resonators can be described by two dimensionless parameters: the Q factor of each resonator and the coupling coefficient κ between the resonators. For the remainder of our analysis we will refer to the absorption Q factor Q_a as simply the Q factor since the scattering Q_s does not play a role in the near-field analysis. The coupling coefficient is a normalized, dimensionless mutual energy metric ranging from zero to one. Strongly interacting resonators will have a coupling coefficient near one, whereas weakly interacting ones will be closer to zero.

Analyzing resonators in terms of Q factors and couplings is used often in microwave filter theory, where the coupling coefficient represents electrical or magnetic coupling between resonators [33]. In this biological context, we are concerned with electrically coupled mechanical resonators. First we will will derive an expression for the coupling coefficient for a simple case of a charged mass spring resonator to gain some intuition about the nature of the coupling. Then we will derive the minimum Q factor needed based on the power transfer efficiency between the resonators.

A. Electrically coupled mechanical resonators

In order to gain insight into the electromechanical coupling coefficient, we analyze the simple case of two coupled mass spring resonators, as depicted in Fig. 3. Each mass carries a charge; therefore, interaction between resonators occurs via the electric field. The resonators are submerged in a fluid medium resulting in drag for each mass.

Let us define $\Delta x(t) = x_1(t) - x_2(t)$. The force induced on resonator 2 by the electric field generated by resonator 1 is given by

$$F_{21} = q_2 E_1 = \frac{q_1 q_2}{4\pi\underline{\epsilon}[r - \Delta x(t)]^2}, \tag{12}$$

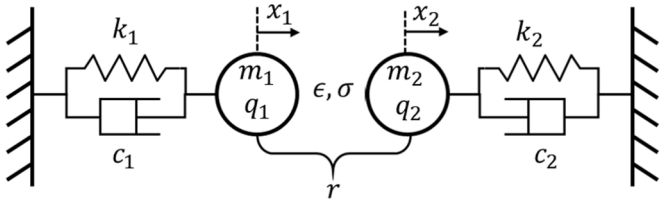

FIG. 3. Coupled spring mass resonators submerged in fluid. Each resonator has mass m, charge q, spring constant k, and damping coefficient c. The medium has permittivity ϵ and conductivity σ. At rest, both resonators are separated by a distance r.

where q_1 and q_2 are the charges of resonators 1 and 2, respectively, r is the distance between the resonators when $\Delta x(t) = 0$, and $\underline{\epsilon} = \epsilon - i\sigma/\omega$.

Assuming that the amplitude variables are much smaller than the distance between the resonators [$r \gg \Delta x(t)$], we can expand Eq. (12) using a Taylor series expansion

$$F_{21} = \frac{q_1 q_2}{4\pi\underline{\epsilon} r^2} - \frac{2q_1 q_2 \Delta x(t)}{4\pi\underline{\epsilon} r^3} + O(\Delta x(t)^2). \tag{13}$$

We note that the first term is constant over time. This DC offset goes to zero because of Debye screening, as explained in Sec. I. Assuming that the oscillations will be very small, we ignore higher powers of Δx and leave ourselves with the dipole approximation. We see that this interdipole force is dependent on the position of both resonators much like a spring connecting both masses. We define this interresonator mutual spring constant as

$$k_m = \frac{q_1 q_2}{2\pi\underline{\epsilon} r^3}. \tag{14}$$

For a mass spring system, the coupling coefficient is defined as [34]

$$\kappa = \frac{k_m}{\sqrt{(k_1 + k_m)(k_2 + k_m)}}. \tag{15}$$

We see that this definition of the coupling coefficient maintains the scaling of the coefficient from 0 to 1. If we assume that both resonators are identical ($q_1 = q_2 = q$ and $k_1 = k_2 = k$) then we can combine Eqs. (14) and (15) to get an expression for κ. If we assume the weak-coupling regime ($k_m \ll k$), then we can also approximate κ as a convenient ratio of electrical to mechanical properties

$$\kappa = \frac{q^2}{q^2 + 2\pi\underline{\epsilon} r^3 k} \approx \frac{q^2}{2\pi\underline{\epsilon} r^3 k}. \tag{16}$$

B. Analyzing the coupling coefficient

In order to get a first-order estimate of what values of κ to expect, we analyze the well-studied example of tubulin. Tubulin is a dimer protein made of α and β tubulin monomers and is the constituent building block of microtubules. In physiological pH, each monomer carries a net charge of five electrons and has a mass of 50 ku [35], though the net charge can vary based on pH and whether the tail region is included [36]. Simulations of the stiffness of tubulin suggest a spring constant of approximately 3.5 N/m [37]. While any potential resonance of the tubulin protein is likely much more complex

than a simple spring mass oscillator, this at least provides a first-order estimate of realistic values of κ. We assume that the frequency is high enough to ignore the effects of conductivity in the medium and assume a relatively close separation distance of 10 nm. Plugging $k = 3.5$ N/m, $q = 8 \times 10^{-19}$ C, $\epsilon = 80\epsilon_0$, and $r = 10$ nm into Eq. (16), we find $\kappa = 4.12 \times 10^{-5}$. This small coupling would permit almost no energy transfer between resonators. Potential biological resonators therefore need a substantially greater charge density in order to permit stronger coupling.

C. Energy transfer between coupled resonators

Coupled-mode theory provides an expression for the maximum possible power transfer efficiency between two coupled resonators, which can also be solved from circuit theory [38,39],

$$\eta = \frac{\kappa^2 Q_1 Q_1}{(1 + \sqrt{1 + \kappa^2 Q_1 Q_2})^2}. \tag{17}$$

For the rest of our analysis, we will assume that the resonators are identical ($Q_1 = Q_2 = Q$). This means that for a system transmitting power P_t, the power absorbed is given by $P_a = \eta P_t$. This expression assumes optimal impedance matching and represents the highest possible power transfer efficiency between the two resonators. From Eq. (5) we know that the energy absorbed is given by $U_{\max} = P_a Q/\omega$. By setting the maximum stored energy equal to the thermal energy ($U_{\max} = k_B T$), as done in Eq. (18), we can solve for Q to get an expression for the minimum necessary Q factor,

$$k_B T = \frac{\eta P_t Q}{\omega}. \tag{18}$$

The explicit solution for Q in Eq. (18) is solvable, though complicated because η is also a function of Q. For the sake of intuition, we can take a Taylor expansion of Eq. (17) about $\kappa = 0$ (for any significant interaction distance $\kappa \ll 1$) and obtain an approximate solution

$$Q_{min} \approx \sqrt[3]{\frac{4 k_B T \omega}{P_t \kappa}}. \tag{19}$$

Unlike the far-field case, this expression for the minimum Q factor is frequency dependent.

The explicit (nonapproximate) form of Eq. (19) is plotted in Fig. 4 for varying values of the coupling strength. The value of the coupling coefficient in the legend is attenuated as a function of frequency by a factor of $|A(\omega)|$, where $A(\omega)$ is defined in Eq. (1). The medium is assumed to have a relative permittivity of 80 and a conductivity of 1.1 S/m. Using the same logic from the far-field case, we limit the source power to the average power output of a cell, $P_t = 10^{-12}$ W [29]. We see that the minimum Q factor is lowest near the plasma frequency, where the oscillation period is longer but the interacting fields are not yet screened.

IV. COMPARISON WITH SIMULATED RESONANCES

We have established general criteria for a resonator to have the possibility of sustaining near- or far-field communication. Far-field communication requires excessively high Q factors at nonthermal power levels and seems unlikely as a communication modality in general. Near-field communication seems likely at frequencies near the plasma frequency, but coupling strengths would need to be particularly high to permit biologically realistic Q factors. To compare our criterion to more practical scenarios, we compare our near-field limit to previously studied biological resonances.

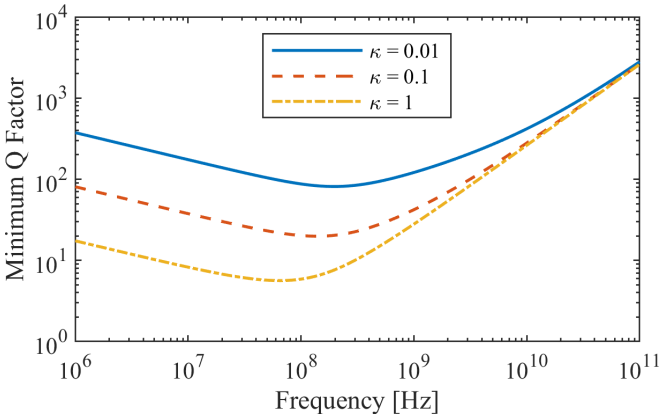

FIG. 4. Minimum Q factor for two identical coupled resonators as a function of frequency for different interresonator coupling strengths κ. We assume that $T = 300$ K and $P_t = 10^{-12}$ W. The value of κ in the legend is attenuated as a function of frequency by a factor of $|A(\omega)|$.

A. Microtubule vibrations

Microtubules have been extensively analyzed in terms of normal modes and vibrations. Microtubules are a ubiquitous component of the cytoskeleton and cilia of eukaryotic cells. They are tubular protein complexes constructed out of α and β tubulin monomers. A considerable amount of research has been been spent studying the mechanical vibrations of microtubules [12,40] and even the resulting electric fields that would be generated by the vibrating polar protein [11,13,41]. No experimental evidence to date has confirmed these high-frequency vibrations. Various computational studies calculate vibrational frequencies on the order of 1–100 GHz, depending on length and material properties [12].

The Q factor of hypothetical microtubule resonances has unfortunately been overlooked by some computational studies. Some work suggests vibrations would be entirely overdamped by surrounding viscous media [42]. As a counterargument, Pokorný suggested that the ion layer around the charged surface of the microtubule would create a slip boundary condition, enhancing the Q factor [43]. Such slip boundaries have been considered analytically in nanoresonators [44]. Only recently has a computational study compared microtubule vibrations with multiple boundary conditions: no damping, a no-slip layer, and a slip layer [45]. Their results suggest that with a no-slip boundary condition, all vibrational modes are overdamped. With the slip layer, only the flexing radial mode is underdamped because of its extremely low amplitude (less than 0.1 Å). The Q factor of this radial mode was calculated to be quite large: 177 at 53 MHz [46]. Because this is a radial

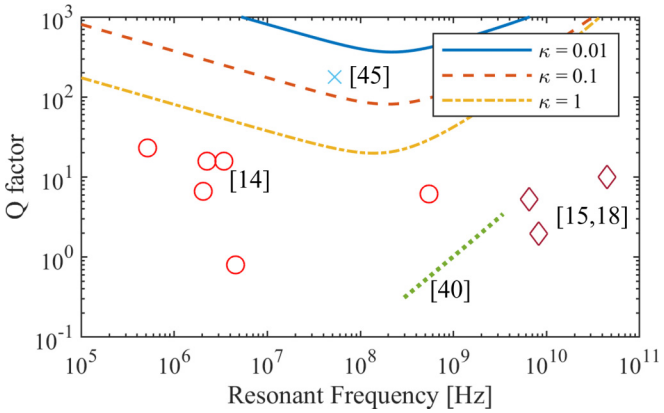

FIG. 5. Minimum Q factor for near-field communication (blue solid line) vs frequency for varying values of κ. The red circles represent the Q factor of calculated bacteria cell membrane resonances for different bacterial species computed in [14]. The green dotted line represents the calculated Q factor of bending microtubule vibrations as a function of the microtubule length computed in [40]. The cyan cross represents the Q factor of the slip layer radial mode calculated in [45]. Finally, the magenta diamonds represent the Q factor of dipolar modes in viruses [15,18].

mode, the resonant frequency is expected to be independent of length, though molecular dynamics studies have suggested this might not be a pure radial mode due to anisotropy [47].

Samarbakhsh and Tuszynski computed the Q factor of the bending mode of microtubules with incident ultrasound waves using analytical beam equation methods [40]. They computed the resonant frequency and Q factor of the bending mode vibration of a 10-m microtubule as a function of mode number. It is expected that shorter microtubules should have higher resonant frequencies. Their data are reproduced and plotted alongside our minimum near-field Q factor in Fig. 5.

B. Cell membranes

Because of its negative charge, the cell membrane is also a candidate for electromechanical coupling. To explore the ultrasound destruction of bacteria, Zinin investigated the Q factor of spherical bacterial cell membranes [14]. Using experimental data to inform cellular mechanical properties, they used an analytical model to estimate the resonant frequency and Q factor of several common bacteria. While some of these Q factors are quite large, most of these resonances are below the typical plasma frequency of cellular media. All of the reported Q factors are plotted alongside our minimum near-field Q factor in Fig. 5. It should be noted that these modes were analyzed under the assumption of ultrasound excitation and it is not guaranteed that EM fields would couple into those modes.

C. Viruses

Many viruses are comprised of spherical or rod-shaped capsid shells with negatively charged DNA or RNA inside. Recognizing the charge concentration in the center of viruses, work has been done investigating how microwaves could couple into the natural vibrational frequencies of the spherical

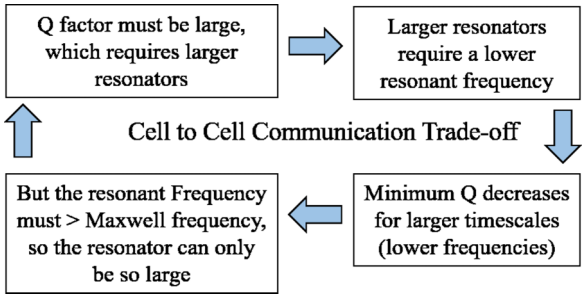

FIG. 6. Diagram illustrating the fundamental trade-off of cell-to-cell communication using electrically coupled mechanical resonators. Essentially, the resonator must be large enough to maintain a large Q factor but not so large as to resonate at a frequency below the plasma frequency.

or rodlike dipolar modes in viruses [16]. These resonances have not only been modeled and simulated, but also measured experimentally and exploited to deactivate viruses at low-power intensities [17,18]. These measured Q factors are plotted in Fig. 5.

V. CONCLUSION

Starting with coupled-mode-theory relationships of energy transfer, we derived the minimum Q factors required for electromagnetic communication to occur between an incoming plane wave and resonator, as well as two resonators with coupled near fields. The key assumption is that the resonator must be able to store more energy from EM interactions than thermal energy. We identified a region where near-field communication would be most efficient and might be sustained, occurring roughly around 100 MHz.

We compared our model with previous studies of the Q factor of microtubule, cell membrane, and virus vibrations. For microtubules, the Q factor of the bending modes is too low to meet our criteria for any coupling strength. The slip-layer radial mode is much more likely to sustain communication because of its large Q. The amplitude of the vibration simulated, however, was very small (less than 0.1 Å), suggesting that the mode might not be able to store much energy and that our transmit power might be an overestimate. Previous simulations on the flexing mode of microtubules have suggested it would be the most electrically active mode, but also that the mutual energy between vibrating microtubules would not exceed the thermal energy [13].

Some cell membrane vibrations also have larger Q factors, but typically occur at frequencies too low to meet our criterion for anything other that maximum coupling. The dipolar resonances of viruses, on the other hand, are at frequencies too high to meet our criterion.

Our analysis suggests that high Q resonances centered around the plasma frequency have the greatest chance of sustaining cellular communication through electromechanical coupling. The simulated slip layer radial vibration in microtubules best meets our criterion. Our analysis also had an implicit power budget of $P_t = 10^{-12}$ W, which might be

too large of an excitation to focus into a single microtubule and still vibrate within the slip layer. More research into the existence and properties of potential slip layers is required to explore their impact on other resonances.

This study revealed a fundamental trade-off for cell-to-cell communication via coupled resonators, which is illustrated in Fig. 6. This relationship is further explored in a simplified model in our Supplemental Material [48]. Essentially, the resonator must be large enough to maintain a large Q factor, but not so large as to resonate below the plasma frequency. This suggests the optimal frequency range for this modality of communication would be just above the plasma frequency for the media.

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[1] M. Cifra, J. Z. Fields, and A. Farhadi, Electromagnetic cellular interactions, Prog. Bioph. Mol. Biol. **105**, 223 (2011).
[2] F. Scholkmann, D. Fels, and M. Cifra, Non-chemical and non-contact cell-to-cell communication: A short review, Am. J. Transl. Res. **5**, 586 (2013).
[3] W. Metcalf and T. Quickenden, Mitogenetic radiation, Nat. Cytol. **216**, 169 (1967).
[4] D. Fels, in *Fields of the Cell*, edited by D. Fels, M. Cifra, and F. Scholkmann (Research Signpost, Trivandrum, 2015), Chap. 9, pp. 149–162.
[5] D. Fels, Cellular communication through light, PLoS ONE **4**, e5086 (2009).
[6] C. Rossi, A. Foletti, A. Magnani, and S. Lamponi, New perspectives in cell communication: Bioelectromagnetic interactions, Semin. Cancer Biol. **21**, 207 (2011).
[7] H. Fröhlich, Bose condensation of strongly excited longitudinal electric modes, Phys. Lett. **26A**, 402 (1968).
[8] H. Fröhlich, Long-range coherence and energy storage in biological systems, Int. J. Quantum Chem. **2**, 641 (1968).
[9] H. Fröhlich, Long range coherence and the action of enzymes, Nature (London) **228**, 1093 (1970).
[10] J. R. Reimers, L. K. McKemmish, R. H. McKenzie, A. E. Mark, and N. S. Hush, Weak, strong, and coherent regimes of Fröhlich condensation and their applications to terahertz medicine and quantum consciousness, Proc. Natl. Acad. Sci. USA **106**, 4219 (2009).
[11] M. Cifra, J. Pokorný, D. Havelka, and O. Kučera, Electric field generated by axial longitudinal vibration modes of microtubule, Biosystems **100**, 122 (2010).
[12] O. Kučera, D. Havelka, and M. Cifra, Vibrations of microtubules: Physics that has not met biology yet, Wave Motion **72**, 13 (2017).
[13] K. A. Thackston, D. D. Deheyn, and D. F. Sievenpiper, Simulation of electric fields generated from microtubule vibrations, Phys. Rev. E **100**, 022410 (2019).
[14] P. V. Zinin, J. S. Allen, and V. M. Levin, Mechanical resonances of bacteria cells, Phys. Rev. E **72**, 061907 (2005).
[15] T.-M. Liu, H.-P. Chen, S.-C. Yeh, C.-Y. Wu, C.-H. Wang, T.-N. Luo, Y.-J. Chen, S.-I. Liu, and C.-K. Sun, Effects of hydration levels on the bandwidth of microwave resonant absorption induced by confined acoustic vibrations, Appl. Phys. Lett. **95**, 173702 (2009).
[16] T.-M. Liu, H.-P. Chen, L.-T. Wang, J.-R. Wang, T.-N. Luo, Y.-J. Chen, S.-I. Liu, and C.-K. Sun, Microwave resonant absorption of viruses through dipolar coupling with confined acoustic vibrations, Appl. Phys. Lett. **94**, 043902 (2009).
[17] S.-C. Yang, H.-C. Lin, T.-M. Liu, J.-T. Lu, W.-T. Hung, Y.-R. Huang, Y.-C. Tsai, C.-L. Kao, S.-Y. Chen, and C.-K. Sun, Efficient structure resonance energy transfer from microwaves to confined acoustic vibrations in viruses, Sci. Rep. **5**, 18030 (2016).
[18] C.-K. Sun, Y.-C. Tsai, Y.-J. E. Chen, T.-M. Liu, H.-Y. Chen, H.-C. Wang, and C.-F. Lo, Resonant dipolar coupling of microwaves with confined acoustic vibrations in a rod-shaped virus, Sci. Rep. **7**, 4611 (2017).
[19] G. S. Edwards, C. C. Davis, J. D. Saffer, and M. L. Swicord, Resonant Microwave Absorption of Selected DNA Molecules, Phys. Rev. Lett. **53**, 1284 (1984).
[20] L. L. Van Zandt, Resonant Microwave Absorption by Dissolved DNA, Phys. Rev. Lett. **57**, 2085 (1986).
[21] M. Cifra, Electrodynamic eigenmodes in cellular morphology, Biosystems **109**, 356 (2012).
[22] R. Phillips, J. Kondev, J. Theriot, and H. Garcia, in *Physical Biology of the Cell*, 2nd ed., edited by S. Scholl (Garland Science, New York, 2013).
[23] J. R. de Xammar Oro, G. Ruderman, and J. R. Grigera, Electrodynamics of interactions in electrolyte media. Possible consequences in biological functions, Biophysics **53**, 195 (2008).
[24] J. Grigera, F. Vericat, G. Ruderman, and J. R. De Xammar Oro, On the threshold frequency of long-range interactions in physiological solutions, Chem. Phys. Lett. **156**, 615 (1989).
[25] R. K. Adair, Vibrational resonances in biological systems at microwave frequencies, Biophys. J. **82**, 1147 (2002).
[26] R. E. Hamam, A. Karalis, J. D. Joannopoulos, and M. Soljačić, Coupled-mode theory for general free-space resonant scattering of waves, Phys. Rev. A **75**, 053801 (2007).
[27] J. Jackson, *Classical Electrodynamics*, 3rd ed. (Wiley, New York, 1998).
[28] H. A. Wheeler, Fundamental limitations of small antennas, Proc. IRE **35**, 1479 (1947).
[29] R. Milo, R. Phillips, and N. Orme, *Cell Biology by the Numbers* (Garland Science, New York, 2016).
[30] FCC Policy on Human Exposure (Federal Communications Commission, Washington, DC, 2015), available at https://www.fcc.gov/general/fcc-policy-human-exposure.
[31] R. K. Adair, Biophysical limits on athermal effects of RF and microwave radiation, Bioelectromagnetics **24**, 39 (2003).

[32] D. Havelka, M. Cifra, O. Kučera, J. Pokorný, and J. Vrba, High-frequency electric field and radiation characteristics of cellular microtubule network, J. Theor. Biol. **286**, 31 (2011).

[33] J.-S. Hong, *Microstrip Filters for RF/Microwave Applications*, 2nd ed. (Wiley, New York, 2011).

[34] D. Newland, Calculation of power flow between coupled oscillators, J. Sound Vib. **3**, 262 (1966).

[35] J. A. Tuszyński, J. A. Brown, E. Crawford, E. J. Carpenter, M. L. A. Nip, J. M. Dixon, and M. V. Satarić, Molecular dynamics simulations of tubulin structure and calculations of electrostatic properties of microtubules, Math. Comput. Model. **41**, 1055 (2005).

[36] P. Marracino, D. Havelka, J. Pruša, M. Liberti, J. Tuszynski, A. T. Ayoub, F. Apollonio, and M. Cifra, Tubulin response to intense nanosecond-scale electric field in molecular dynamics simulation, Sci. Rep. **9**, 10477 (2019).

[37] M. A. Deriu, M. Soncini, M. Orsi, M. Patel, J. W. Essex, F. M. Montevecchi, and A. Redaelli, Anisotropic elastic network modeling of entire microtubules, Biophys. J. **99**, 2190 (2010).

[38] K. A. Thackston, H. Mei, and P. P. Irazoqui, Coupling matrix synthesis and impedance-matching optimization method for magnetic resonance Coupling systems, IEEE Trans. Microwave Theory Tech. **66**, 1536 (2018).

[39] M. Kesler, Highly resonant wireless power transfer: Safe, efficient, and over distance, WiTricity report (WiTricity Corporation, Watertown, 2017), available at https://witricity.com/wp-content/uploads/2016/12/White_Paper_20161218.pdf.

[40] A. Samarbakhsh and J. A. Tuszynski, Vibrational dynamics of bio- and nano-filaments in viscous solution subjected to ultrasound: Implications for microtubules, Eur. Biophys. J. **40**, 937 (2011).

[41] D. Havelka, O. Kučera, M. A. Deriu, and M. Cifra, Electro-acoustic behavior of the mitotic spindle: A semi-classical coarse-grained model, PLoS ONE **9**, e86501 (2014).

[42] K. R. Foster and J. W. Baish, Viscous damping of vibrations in microtubules, J. Biol. Phys. **26**, 255 (2000).

[43] J. Pokorný, Viscous effects on polar vibrations in microtubules, Electromagn. Biol. Med. **22**, 15 (2003).

[44] O. Krivosudský and M. Cifra, Microwave absorption by nanoresonator vibrations tuned with surface modification, Europhys. Lett. **115**, 44003 (2016).

[45] S. Li, C. Wang, and P. Nithiarasu, Simulations on an undamped electromechanical vibration of microtubules in cytosol, Appl. Phys. Lett. **114**, 253702 (2019).

[46] S. Li (private communication).

[47] D. Havelka, M. A. Deriu, M. Cifra, and O. Kučera, Deformation pattern in vibrating microtubule: Structural mechanics study based on an atomistic approach, Sci. Rep. **7**, 4227 (2017).

[48] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevE.101.062401 for an analysis estimating the approximate Q factor of a generic biological resonator.