

# An Information-Theoretic Model and Analysis of Graphene Plasmon-Assisted FRET-Based Nanocommunication Channel

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## ABSTRACT

Nanoscale communication based on Förster Resonance Energy Transfer (FRET) enables single molecular nanomachines to communicate by transferring their optical excited states, i.e., excitons, between each other. Our recent studies revealed that FRET is a practical solution for short-range nanocommunications at very high rates. However, it was also proven that the reliability seriously degrades when the distance between communicating fluorophores exceeds the critical Förster radius which is around 10nm.

In this study, we propose to exploit Graphene Plasmons (GPs) incorporated with excitons as the information carriers between two distant fluorescent molecules. The interaction between the optical excitons and graphene plasmons is a newly explored phenomenon, and this is the first study that approaches this phenomenon from the communication theoretical perspective. In this paper, we derive an analytical expression for the point-to-point channel capacity, and investigate the effect of fundamental system parameters on the channel performance. We show that information can be transmitted reliably through distances over 500nm with acceptable communication rates.

## Keywords

Nanocommunications, FRET, graphene plasmon, channel capacity

## 1. INTRODUCTION

Nanotechnology has enabled manufacturing of nano-size machines such as nano-robots, nanosensors, nano-logic gates which are able to perform simple actuating, sensing and computing operations. Forming nanonetworks by enabling coordination through communication among them is envisioned to significantly enhance their operational capabilities. Therefore, realizing communication at nanoscale is of crucial importance for groundbreaking medical, environmental

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and industrial nanotechnology applications. Nanocommunications have been approached from several perspectives such as molecular [1], acoustic [6], or electromagnetic [2], some of which are bio-inspired. In addition to these approaches, we proposed a radically different communication technique based on Förster Resonance Energy Transfer (FRET) observed among fluorescent molecules, e.g., organic dyes, fluorescent proteins, and Quantum Dots (QDs) [11].

FRET is a well-known quantum mechanical phenomenon which defines the non-radiative resonant transfer of excitons from an excited donor fluorophore to a ground state fluorophore based on the near-field Coulomb interaction between them [15]. It is widely observed in photosynthesis during the coherent transmission of absorbed optical energy to reaction center [3]. The phenomenon has been extensively used in biotechnological applications ranging from fluorescence microscopy to biosensing and nanomedicine. For example, based on the FRET mechanism, QDs have been proposed as efficient photosensitizers for photodynamic therapy (PDT) of cancer [18]. Moreover, single molecular logic gates have been designed exploiting the FRET phenomenon, which underlines its potential for molecular information processing [16]. Recently, we proposed to use FRET as a communication means between single-fluorophore-based nanomachines, and analyzed its performance for several channel configurations such as point-to-point, broadcast and relay [12]-[14]. We also studied FRET-based mobile ad hoc nanonetworks, and showed its potential for in-vivo biosensing applications [13]. However, the range of FRET and FRET-based nanocommunication is very limited since it is based on the weak Coulomb interaction of fluorophores, which strongly degrades for intermolecular distances larger than Förster radius, e.g., 2-10nm.

Our approaches from the communications perspective to resolve this problem theoretically resulted in a communication range of approximately 200nm by applying longer excitation pulses, and employing a large concentration of fluorescent molecules as the relay nodes [14]. Besides our studies, several attempts have been made to increase the range of FRET. A large body of work has been focused on the enhancement of transfer efficiency and range near the metal interfaces. The underlying mechanism of this phenomenon is the intermediation of the Surface Plasmon Polaritons (SPPs) to carry the exciton energy over larger distances [10]. In

other words, an excited donor fluorophore in the close vicinity of a metal-air interface excites SPPs, and the excited SPPs traveling through the two dimensional interface transfer their energy to a nearby acceptor fluorophore through a near-field interaction. However, the ohmic losses intrinsic to the metallic interfaces limits this enhancement of range. Recently, this phenomenon is revisited by employing Graphene Plasmons (GPs) as the intermediaries of energy transfer, and it is theoretically demonstrated that the transfer efficiency can be increased by a factor of  $10^4$  over distances larger than 500nm [21].

Graphene plasmonics is a newly emerging research area, and fundamentally differs from the metal plasmonics by offering significant advantages in terms of lower plasmonic losses resulted from the weaker electron-phonon interactions [17]. Another intrinsic advantage of GPs over metallic SPPs is the adjustability of the extent of strong electromagnetic energy confinement through electrical gating or chemical doping. However, a fundamental problem arises from the weak coupling of freely propagating photons to graphene plasmons which does not allow the direct optical excitation of plasmons [8]. The very first studies on the exciton-GP interactions originates from this limitation, such that, using semiconductor fluorescent molecules like Quantum Dots (QDs) as nanoscale tips was proposed to excite GPs through near-field interaction, and the strong coupling between GPs and excitons was underlined [20]. Moreover, the long-range coupling of QD emitters near the graphene interface was also demonstrated in [7]. Furthermore, GPs begin to find applications in nanocommunications by allowing the design of graphene-based nanoantennas for communication in THz band [9].

In this article, for the first time in the literature, we investigate the phenomenon of exciton-GP coupling from the information theoretical perspective. We propose and analytically model a point-to-point nanocommunication channel between a single pair of QD molecules immobilized on a two-dimensional chemically doped graphene sheet through aptamers. We assume that binary ON/OFF Keying modulation is utilized, and the information is represented by finite optical pulses. Employing GPs as the intermediaries for information transfer from a donor QD as the nanotransmitter to an acceptor QD as the nanoreceiver which are distantly located, we derive an analytical expression for the capacity of this communication channel. Based on the channel capacity, we analyze the channel's performance for varying system design parameters such as the excitation pulse length and intermolecular distance, and intrinsic parameters of graphene and QDs such as the QD's radiative lifetime and electron scattering rate of graphene. We aim to reveal the effect of each controllable parameter on the communication performance. We arrive at the conclusion that reliable communication is possible through intermolecular distances over 500nm with relatively high communication rates by properly adjusting the system parameters.

The proposed communication channel promises for a wide variety of nanotechnology applications. For example, the outputs of a number of fluorescent biosensors which are capable of detecting single molecular targets, and dispersed on a graphene surface can be rapidly transferred to a reaction

center, e.g., fluorophore-based singlet oxygen synthesizers, for real-time acting. Moreover, it can enable high-rate information processing through nanoscale FRET-based logic gates when the system is powered by a remote optical source. It also constitutes an optical interface between nanoscale and macroscale operations.

The remainder of the paper is organized as follows. In Section II, we present the system model, and derive the channel capacity. Numerical analyses for channel performance are presented in Section III. Finally, the concluding remarks are given in Section IV.

## 2. CHANNEL MODEL

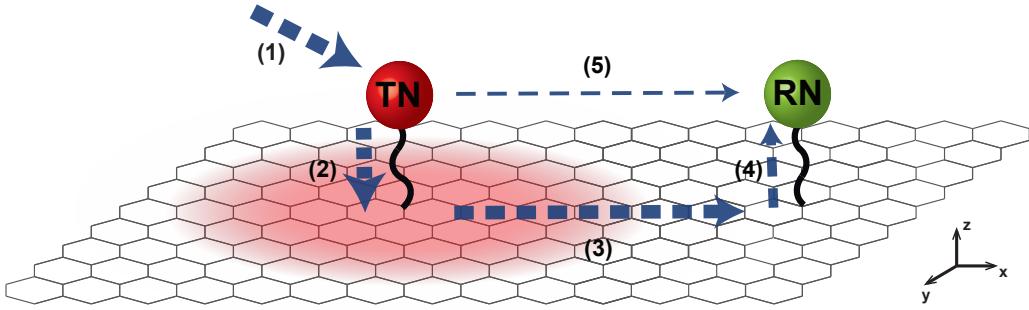
The proposed nanocommunication channel is conceptually demonstrated in Fig. 1. A QD pair is located in the close proximity of the graphene. The QDs have different but similar optical characteristics, such that, one of them is acting as energy donor, and the other one is acting as energy acceptor. The emission spectrum of the donor and the absorption spectrum of the acceptor have a considerable overlap such that resonant energy transfer between them is possible. We consider that binary ON/OFF Keying modulation is employed. The information is encoded into the excited state of the QDs, such that excited state represents bit-1, and ground state represents bit-0.

The donor QD is the nanotransmitter of the system which is powered by a remote optical source with a wavelength belongs to its absorption spectrum. The optical source can be either an information source which sends the information to the donor QD, i.e., nanotransmitter, by means of finite length optical pulses, or a power source which continuously excites the donor and allows it to switch on and off in the context of biosensing operation. The excited nanotransmitter is expected to generate longitudinal plasmons on the graphene surface which can travel a certain distance depending on the system parameters. The plasmons that succeed to arrive to the proximity of the acceptor QD, i.e., nanoreceiver, are expected to excite the acceptor. The donor QD can also directly excite the acceptor QD through the classical FRET mechanism, or it can relax through fluorescence. We assume that the nanoreceiver can detect bit-1 when it receives at least one exciton during the transmission of bit-1.

In the following, we analytically model information transmission through the channel, and derive the information theoretic capacity. The transmission of bit-1 relies on the transfer of the generated excitons on the nanotransmitter to the nanoreceiver through the plasmonic channel. In order to express the probability of successful transmission of bit-1, it is imperative to begin with the derivation of the transfer probability of single generated exciton.

### 2.1 Probability of Energy Transfer

An excited fluorescent molecule, e.g., QD, relaxes to the ground state after a random duration through radiative or non-radiative energy loses. While radiative loses are directly related to the intrinsic characteristics of the fluorophore, e.g., fluorescence rate, non-radiative loses mostly depend on the electromagnetic interactions within the molecular proximity [15]. For the nanotransmitter in our system, the exci-



**Figure 1:** The conceptual design of plasmon-assisted FRET-based communication channel on a graphene sheet. Arrow (1) denotes the excitation power, (2) denotes the total power transferred to the graphene, (3) is the power of the generated GPs traveling through graphene, (4) is the power transferred to the acceptor QD by the GPs, (5) is the transferred power through direct FRET mechanism.

tation power is dissipated through three distinct ways:

$$P_{Total}(w) = P_0(w) + P_G(w) + P_{FRET}(w) \quad (1)$$

where  $w$  is the angular frequency,  $P_0(w)$  is the radiative power loss of the donor in the form of released photons.  $P_G(w)$  denotes the power dissipated in the graphene, and  $P_{FRET}(w)$  is the power transferred to the acceptor. The acceptor can receive the excitation power from the donor in two different ways, it can be either directly excited by the classical FRET as a result of the Coulomb interaction via free space, or indirectly through the plasmonic channel:

$$P_{FRET}(w) = P_{FRET,D}(w) + P_{FRET,G}(w) \quad (2)$$

$P_{FRET,D}(w)$  and  $P_{FRET,G}(w)$  represent the received power by the acceptor through direct FRET, and through graphene plasmons, respectively. The overall efficiency of the energy transfer can be calculated by integrating the ratio of the power received by the acceptor to the initial excitation power, which equals to the total dissipated power, over all frequencies.

$$E_{FRET} = \int \frac{P_{FRET}(w)}{P_{Total}(w)} f_d(w) dw \quad (3)$$

Here,  $f_d(w)$  is the normalized emission spectral function of the donor QD.

Considering at the quantum level, the probability of a single exciton generated on the donor to be transferred to the acceptor is equal to the transfer efficiency, i.e.,  $Pr[FRET] = E_{FRET}$  [11].

The radiative loss of the donor can be given by

$$P_0(w) = \frac{\mu_d^2 w^4}{3c^3 Q_d} \quad (4)$$

where,  $\mu_d$  is the amplitude of the donor's transition dipole moment,  $Q_d$  is the quantum yield of the donor, and  $c$  is the speed of light. The power non-radiatively dissipated in the graphene is given in [21] by

$$P_G(w) = \frac{\mu_d^2 w q_p^3}{3\kappa} e^{-2q_p|z_d|} \quad (5)$$

where  $q_p$  is the wavenumber,  $\kappa$  is the effective dielectric constant of the medium, and  $z_d$  is the distance of the donor QD to the graphene surface.

The power transferred to the acceptor as a result of direct FRET is given by

$$P_{FRET,D}(w) = \frac{w}{3} \mu_d^2 \text{Im}[\alpha_a(w)] R_{ad}^{-6} \quad (6)$$

where  $R_{ad}$  is the intermolecular distance between the donor and acceptor QDs,  $\alpha_a(w)$  is the dipole polarizability of the acceptor. The imaginary part of the dipole polarizability can be related to the absorption cross section of the acceptor  $\sigma_a$  by

$$\text{Im}[\alpha_a(w)] = \frac{3c\sigma_a}{4\pi w} \quad (7)$$

For intermolecular distances exceeding the characteristic Förster radius, the energy transfer occurs mainly through the plasmonic channel. The transferred power by the graphene plasmons is expressed in [21] as

$$P_{FRET,G}(w) = \frac{8\pi\mu_d^2 w \text{Im}[\alpha_a(w)] q_p^5}{9\kappa^2 R_{ad}} \times e^{-(R_{ad}/R_p) - 2q_p(|z_a| + |z_d|)} \quad (8)$$

where  $z_a$  is the distance between the acceptor QD and the graphene, and  $R_p$  is the characteristic travel length of the graphene plasmons.

## 2.2 Graphene Plasmon Wavenumber and Plasmon Travel Length

Plasmon wavenumber and travel length are the key parameters that determine the extent of the exciton transfer probability, however, for doped graphene, to the best of our knowledge no exact analytical expressions for them have been derived so far. In this paper, we compute them numerically based on the density correlation function of the doped graphene.

The bare density correlation function of the graphene is ex-

pressed as

$$\begin{aligned} \Pi(q, w) = & -\frac{g_s g_v \epsilon_F}{2\pi \hbar^2 v_F^2} - i\pi \frac{F(q, w)}{\hbar^2 v_F^2} + \frac{F(q, w)}{\hbar^2 v_F^2} \\ & \times \left\{ G\left(\frac{\hbar w + 2\epsilon_F}{\hbar v_F q}\right) - \Theta\left(\frac{2\epsilon_F - \hbar w}{\hbar v_F q} - 1\right) \right. \\ & \times \left[ G\left(\frac{2\epsilon_F - \hbar w}{\hbar v_F q}\right) - i\pi \right] \\ & \left. - \Theta\left(\frac{\hbar w - 2\epsilon_F}{\hbar v_F q} + 1\right) \times G\left(\frac{\hbar w - 2\epsilon_F}{\hbar v_F q}\right) \right\} \end{aligned} \quad (9)$$

where  $g_s$  is the spin degeneracy,  $g_v$  is the valley degeneracy,  $\hbar$  is the reduced Planck constant,  $v_F$  and  $\epsilon_F$  are the Fermi velocity and Fermi level, respectively [22].  $\Theta(\cdot)$  stands for the Heaviside step function, and the functions  $G(\cdot)$  and  $F(\cdot)$  are defined as

$$F(q, w) = \frac{g}{16\pi} \frac{\hbar v_F^2 q^2}{\sqrt{w^2 - v_F^2 q^2}} \quad (10)$$

$$G(x) = x\sqrt{x^2 - 1} - \ln\left(x + \sqrt{x^2 - 1}\right) \quad (11)$$

The Fermi velocity is calculated using

$$v_F = \frac{3at}{2\hbar} \quad (12)$$

where  $a = 0.142\text{nm}$  is the carbon-carbon bond length for graphene,  $t = 2.7\text{eV}$  is the nearest neighbor hopping energy, and resulting  $v_F = 8.73 \times 10^5 \text{m/s}$  [22].

In order to account for the losses due to electron scattering in doped graphene, adapting the Mermin procedure, the modified bare density correlation function can be written as [21]

$$\Pi_\gamma(q, w) = \frac{(1 + i\gamma/w)\Pi(q, w + i\gamma)}{1 + (i\gamma/w)\Pi(q, w + i\gamma)/\Pi(q, 0)} \quad (13)$$

where  $\gamma$  is the electron scattering rate. The full density correlation function of graphene within the Random Phase Approximation (RPA) is then given by

$$\Pi_{RPA}(q, w) = \frac{\Pi_\gamma(q, w)}{1 - v(q)\Pi_\gamma(q, w)} \quad (14)$$

where  $v(q) = e^2/2\kappa q$  is the in-plane Coulomb potential.

Using the same procedure in [21], the plasmon wavenumber  $q_p(w)$  is calculated as the value that makes the denominator of (13) equal to zero. Using the found  $q_p(w)$  for infinitely small frequency intervals, the plasmon travel length  $R_p(w)$  is calculated by numerically solving the following equation

$$R_p(w) = -\frac{\frac{\partial}{\partial q} \{v(q)\text{Re}[\Pi_\gamma(q, w)]\} \Big|_{q=q_p(w)}}{v(q_p(w))\text{Im}[\Pi_\gamma(q_p(w), w)]} \quad (15)$$

### 2.3 Transition Probabilities and Channel Capacity

After we find the transfer probability of single exciton, we now proceed by investigating the collective behavior of excitons. Before doing that, we need to express the number of generated excitons for an optical pulse with a given length.

An excited fluorescent molecule cannot be re-excited until it relaxes to the ground state. The occupation time of the excitons on a fluorescent molecule, i.e., the excited state lifetime or the time between two consecutive generations of excitons, is an exponential random variable [15]. Additionally, we know that exciton generations are independent events [15]. Therefore, the exciton generation is described by a Poisson process.

The generation rate is equal to the total loss rate of the excitons. Therefore, for the donor QD in our system, the generation rate of excitons can be expressed as the sum of the exciton loss rates through three distinct pathways

$$k_e = k_0 + k_G + k_{FRET} \quad (16)$$

where  $k_0$  is the intrinsic radiative relaxation rate,  $k_G$  is the loss rate of excitons in the graphene, and  $k_{FRET}$  is the exciton transfer rate to the acceptor QD. The mean of the excited state lifetime is then given as  $\mu_\tau = 1/k_e$ .

The intrinsic radiation rate is specific to the employed donor molecule, however, the loss rates of excitons to graphene and to acceptor rely on the system parameters. The total dissipation rate of excitons can be derived from the given radiation rate as follows

$$k_0/k_e = Pr[Fluo] = \int \frac{P_0(w)}{P_{Total}(w)} f_d(w) dw \quad (17)$$

where  $Pr[Fluo]$  is the probability of radiation, i.e., fluorescence, for a single exciton.

Since the exciton generation is a Poisson process, the number of generated excitons  $N_e$  under an excitation with a pulse length  $\tau_P$  is a random variable with Poisson distribution, of which mean is  $\mu_e = \tau_P k_e$ . Therefore, its probability mass function (pmf) can be expressed by

$$Pr[N_e(\tau_P) = n] = \frac{e^{-\mu_e} (\mu_e)^n}{n!} \quad (18)$$

Using pmf for the number of generated excitons and the transfer probability expression for a single exciton, we can now derive the successful transmission probability of bit-1, i.e.,  $Pr[Y = 1|X = 1]$ . Since the transfer of at least one exciton to the acceptor is sufficient for the successful detection of bit-1, for a given number of generated excitons  $n$ , the conditional detection probability can be expressed by

$$Pr[Y = 1|X = 1, N_e = n] = 1 - (1 - Pr[FRET])^n \quad (19)$$

and the detection probability of bit-1 is given as

$$\begin{aligned} Pr[Y = 1|X = 1] &= \sum_{n=0}^{\infty} Pr[Y = 1|X = 1, N_e = n] Pr[N_e(\tau_P) = n] \\ &= \sum_{n=0}^{\infty} (1 - (1 - Pr[FRET])^n) \frac{e^{-\mu_e} (\mu_e)^n}{n!} \end{aligned} \quad (20)$$

For the transmission of bit-0, the donor QD is not excited for a specified bit interval which equals to the length of the pulse used for bit-1, i.e.,  $\tau_P$ . We assume that there is no other

**Table 1: Simulation Parameters**

Electron scattering rate ( $\gamma$ )	$10\text{ps}^{-1}$
Dielectric coefficient ( $\kappa$ )	1
Fermi level ( $\epsilon$ )	$0.6\text{eV}$
Donor's and acceptor's distance to graphene ( $z_d, z_a$ )	3nm
Intrinsic radiative lifetime of donor	5ns
Quantum yield of donor ( $Q_d$ )	$10^{-2}$
Absorption cross section of acceptor ( $\sigma_a$ )	$0.02\text{nm}^2$
Length of pulse representing bit-1 ( $T_p$ )	$1\mu\text{s}$
Central frequency of donor's emission ( $w_{c,d}$ )	$0.60\text{eV}/\hbar$
Central frequency of acceptor's absorption ( $w_{c,d}$ )	$0.55\text{eV}/\hbar$
FWHM ( $\Delta_d, \Delta_a$ )	$0.10\text{eV}/\hbar$
Spin/valley degeneracy for graphene ( $g_s, g_v$ )	2

excitation source in the system except the optical source. Therefore, it is not possible for the acceptor QD to be excited during the transmission of bit-0, and we can conclude that  $Pr[Y = 0|X = 0] = 1$ .

Given the transition probabilities and system characteristics, the channel is information-theoretically well-defined as a discrete memoryless Z-channel [4].

The capacity of the channel is the mutual information maximized over all input distributions, and can be analytically expressed as

$$C_Z(p) = \log_2 \left( 1 + 2^{-s(p)} \right) \quad (21)$$

where  $p = 1 - P[Y = 1|X = 1]$  is the probability of failure [19].  $s(p) = h(p)/(1 - p)$ , where  $h(\cdot)$  is the binary entropy function.

### 3. NUMERICAL ANALYSIS

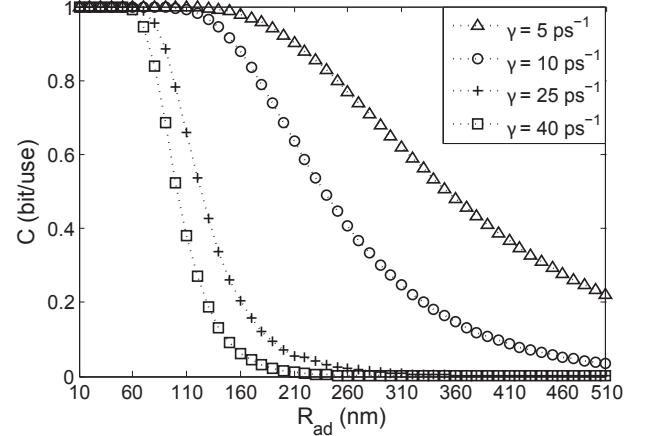
As seen in the derivation of channel capapacity, the communication performance of the plasmon-FRET channel relies on several parameters such as the intrinsic characteristics of the employed fluorescent molecules and graphene, or the system parameters related to the applied optical pulse and the location of transmitter and receiver nodes relative to each other and to the graphene.

In this section, we analyze the channel performance by means of information theoretical capacity with varying critical design parameters. Note that, the plasmon travel length and wavenumber are numerically calculated for each configuration.

The default system setting used in the simulations is summarized in Table 1. We assume that PbSe QDs with different spectral characteristics are employed for the nanotransmitter and nanoreceiver. The spectral density functions of the QDs are approximated by Lorentzian line shape:

$$f_i(w) = \frac{1}{1 + \left( \frac{w - w_{c,i}}{\Delta_i/2} \right)^2} \quad (22)$$

where  $w_{c,i}$  is the central frequency, and  $\Delta_i$  is the Full-Width Half-Maximum (FWHM) of the spectrum, for  $i \in \{d, a\}$  de-



**Figure 2: Channel capacity for different electron scattering rates  $\gamma$  with varying  $R_{ad}$ .**

noting the donor and acceptor. For the selected values in Table 1, Förster radius between donor and acceptor  $R_0$  is approximately 8nm which is a common result for semiconductor fluorescent molecules [15].

### 3.1 Effect of Intermolecular Distance

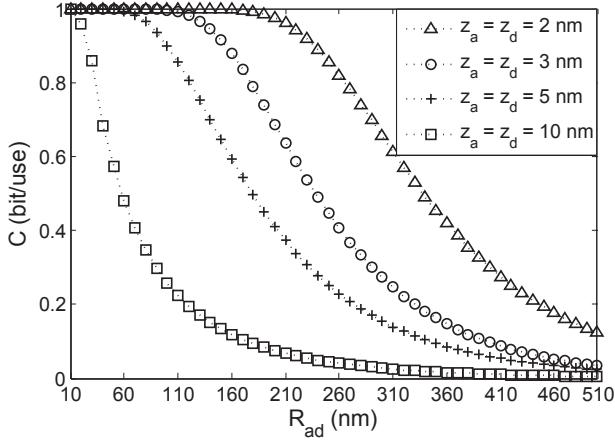
We begin our analysis by investigating the effect of the most critical system parameter, i.e., intermolecular distance between the nanotransmitter and nanoreceiver QDs  $R_{ad}$ . In Figs. 2-5, for different settings, the channel capacity with varying  $R_{ad}$  is demonstrated.

The near-field Coulomb interaction between the donor and acceptor QDs strongly degrades over a certain critical distance whose extent mainly relies on the spectral similarity. The Förster theory on the resonance energy transfer states that the probability of energy transfer depends on the inverse sixth power of the intermolecular distance [5]. Therefore, pure FRET mechanism can be effective up to  $2R_0$ , which is approximately 16nm for the employed fluorophores. For intermolecular distances over  $2R_0$ , the energy transfer is dominated by the graphene plasmons excited by the donor QD, and the ultimate energy transfer range strongly depends on the plasmonic characteristics of the system such as the plasmon travel length  $R_p$ , and the electron scattering rate  $\gamma$  and the doping level  $\epsilon_F$  of graphene.

In the following analyses, we see that as the plasmon travel length is improved by the system parameters, the range of the information transfer also increases, which make it possible for nanotransmitter and nanoreceiver to communicate over greater distances.

### 3.2 Effect of Electron Scattering Rate

Electron scattering rate is a measure of how fast the excited carriers in the form of plasmons lose their energy. Therefore, it sets a limit on the graphene carrier mobility. It is one of the intrinsic characteristics of graphene, and directly related to the impurities and defects on the graphene surface, and the frequency of electron-plasmon coupling, and interactions with the acoustical or optical phonons [8].



**Figure 3:** Channel capacity for different graphene to QD distances  $z_a = z_d$  with varying  $R_{ad}$ .

The electron scattering rate of graphene strongly affects the characteristic travel length of plasmons. High scattering rates result in significant loss of graphene plasmons excited by the donor QD before reaching to the acceptor's proximity. Therefore, the probability of exciton transfer is reduced, and the channel's reliability decreases. This can be easily deduced from Fig. 2. For an intermolecular distance of 160nm, the capacity decreases to 0.05bit/use from 1bit/use, when the graphene's scattering rate is increased by 8-fold. Hence, employing clean samples of graphene, and properly choosing the geometrical parameters resulting in low scattering rates is of great importance for communication purposes.

### 3.3 Effect of QD-Graphene Distance

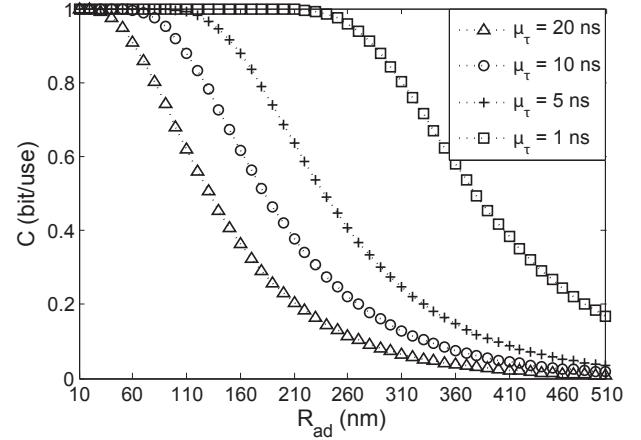
Another important system parameter is the distance of the donor and acceptor QDs to the graphene sheet. The effect of the QD-graphene distance on the channel capacity is demonstrated in Fig. 3. As is seen, the increased distance significantly decreases the channel capacity. The reason behind this is twofold.

As can be deduced from the power dissipation equations, the extent of the electromagnetic interaction between the graphene and QDs increases when QDs get into the proximity of the graphene. Stronger interaction indicates that donor QD can excite more plasmons on the graphene, and the probability of generated graphene plasmons to excite the ground-state acceptor increases with the decreased distance.

As the graphene and donor QD get into closer proximity of each other, the energy loss of the donor to the graphene also increases, therefore, the lifetime of the generated excitons on the donor decreases. Thus, more excitons are generated on the donor during a single pulse which results in the increase of successful transmission probability of bit-1.

### 3.4 Effect of Donor's Radiative Lifetime

The intrinsic excited state lifetime of the donor QD determines the occupation time of the generated excitons on the donor. Since more than one exciton cannot exist at the same time on the same molecule, an excited fluorophore needs to



**Figure 4:** Channel capacity for different mean excited state lifetimes  $\mu_\tau$  with varying  $R_{ad}$ .

return to the ground state to accept the next exciton. Therefore, as the excited state lifetime of the donor decreases, the generation rate of the excitons increases. Since more excitons are generated on the system given a pulse length, the transition probability of bit-1 increases, which also extends the channel capacity.

The effect of the lifetime can be seen in Fig. 4. The selected values lies in the range of common fluorophore lifetimes. As is seen, the channel capacity is significantly improved with the reduced lifetime, i.e., increased exciton generation rate.

### 3.5 Effect of Excitation Pulse Length

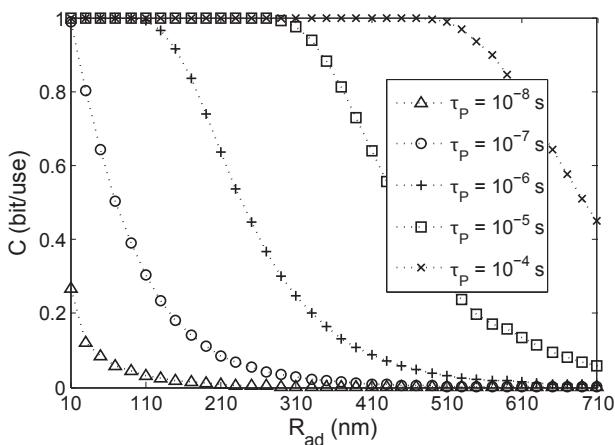
The length of the optical pulse representing bit-1, i.e.,  $\tau_P$  directly affects the number of generated excitons. For longer excitations, more excitons are generated on the donor QD which extends the reliable transition probability of bit-1.

In Fig. 5, the capacity of the channel for varying  $R_{ad}$  with different pulse lengths, ranging from 10ns to 100μs, is demonstrated. As is seen, the channel capacity is significantly improved by applying longer pulses. While the range of the noiseless communication is approximately 150nm for  $\tau_P = 1\mu\text{s}$ , it increases up to 510nm for  $\tau_P = 100\mu\text{s}$ . However, as the pulse length is increased, the information transmission rate decreases. As in the most of the communication systems, this trade-off between the reliable and high-rate communication should be carefully considered depending on the requirements of the application.

Assuming the bit interval is equal to the pulse length, it is possible for nanonodes in the proximity of graphene to reliably communicate through 150nm at a rate of 1Mbps, and through 510nm at a rate of 10kbps. These rates achievable with the combined plasmon-exciton system are significantly higher than one of free-space FRET-based nano-communication channel [12].

## 4. CONCLUSION

In this paper, we propose and analysis an FRET-based nano-communication channel exploiting graphene plasmons as the



**Figure 5:** Channel capacity for different excitation pulse lengths  $\tau_p$  with varying  $R_{ad}$ .

intermediaries for information transfer. We analyze the performance of the channel with varying channel parameters by means of information theoretical capacity, and theoretically prove that the reliable communication range can be extended to distances over 500nm with an acceptable communication rates by properly selecting/configuring the system parameters.

## 5. ACKNOWLEDGMENTS

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