# Graphene-based Plasmonic Nano-transceiver for Terahertz Band Communication

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***Abstract*—In this paper, a plasmonic nano-transceiver for wireless communication in the Terahertz Band (0.1-10 THz) is proposed, modeled and analyzed. The nano-transceiver is based on a High Electron Mobility Transistor (HEMT) built with a III-V semiconductor and enhanced with graphene. In transmission, when a voltage is applied between the HEMT drain and source, electrons are accelerated at the HEMT channel. This movement of electrons results in the excitation of a plasma wave which, on its turn, induces a Surface Plasmon Polariton (SPP) wave on the graphene-based gate. The reciprocal behavior is achieved in reception. The performance of the proposed nano-transceiver is analytically investigated in transmission by coupling the hydrodynamic equations that govern the generation of plasma waves in the HEMT, with the dynamic complex conductivity of graphene and the Maxwell's equations. Numerical results show that the proposed nano-transceiver can effectively generate the necessary SPP wave to drive a plasmonic nano-antenna at Terahertz Band frequencies. Moreover, the utilization of the same nanomaterial as in the plasmonic nano-antennas is expected to ease the transceiver-antenna integration and opens the door to tunable compact nano-transceivers for Terahertz Band communication.**

***Index Terms*—Transceiver, Terahertz Band, Plasmonics, Graphene, Nanonetworks**

## I. Introduction

Nanotechnology is providing a new set of tools to the engineering community to create nanoscale components which are able to perform simple specific tasks, such as computing, data storing, sensing and actuation. The integration of several of these nano-components into a single entity will enable the development of more advanced nano-devices. By means of communication, these nano-devices will be able to achieve complex tasks in a distributed manner [1]. The resulting nanonetworks will enable unique applications in the biomedical, industrial and military fields, such as advanced health monitoring systems, nanosensor networks for biological and chemical attack prevention, or wireless network on chip systems for very large multi-core computing architectures.

For the time being, the communication options for nano-devices are very limited. The miniaturization of a conventional metallic antenna to meet the size requirements of the nano-devices would impose the use of very high operating frequencies (hundreds of Terahertz). The available transmission bandwidth increases with the antenna resonant frequency, but so does the propagation loss. Due to the expectedly very limited power of nano-devices [2], the feasibility of nanonetworks would be compromised if this approach were followed. In addition, it is not clear how a miniature transceiver could be engineered to operate at such very high frequencies.

Alternatively, new types of nano-antennas can be developed by exploiting the unprecedented properties of nanomaterials. Amongst others, graphene, i.e., a one-atom-thick layer of carbon atoms in a honeycomb crystal lattice [3], [4], supports the propagation of Surface Plasmon Polariton (SPP) waves at frequencies as low as in the Terahertz Band (0.1-10 THz). Starting from the properties of the SPP waves, plasmonic nano-antennas for Terahertz Band communication have been recently proposed [5], [6], [7]. These nano-antennas are just tens of nanometers wide and few micrometers long, and can be easily integrated in nano-devices.

In addition to the antenna, Terahertz Band signal generators and detectors are necessary to enable ultra-broadband wireless communication. Existing Terahertz radiation sources such as Quantum Cascade Lasers (QCLs) and frequency up-converters are usually too big, require external lasers for optical electron pumping, and perform poorly at room temperature [8], [9]. Similarly, existing Terahertz Band radiation detectors, e.g., Schottky diodes and bolometers [10], [11], are not suitable for ultra-broadband communication networks among nano-devices due to their size, performance at room temperature, and maximum modulation bandwidth.

Recently, compact signal generators and detectors have been developed by using a single High Electron Mobility Transistor (HEMT) based on III-V semiconductors, e.g., Gallium Nitride (GaN), Gallium Arsenide (GaAs) or Indium Gallium Arsenide (InGaAs) [12], [13], [14]. In particular, it has been shown that plasma waves at Terahertz Band frequencies can be excited in the channel of a HEMT with nanometric gate length by means of either electrical or optical pumping. At cryogenic temperatures, the periodic excitation of the electrons results in well-defined resonant plasma waves. However, at room temperature, plasma waves tend to be overdamped, and the performance as a source and as a detector drastically decreases. Moreover, the efficiency in the coupling of the generated signals with a radiating antenna remains unclear.

In this paper, we propose, model and analyze a graphene-

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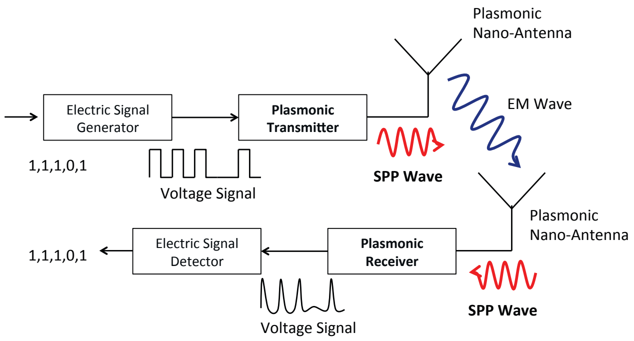



Fig. 1. Conceptual nano-transceiver architecture.

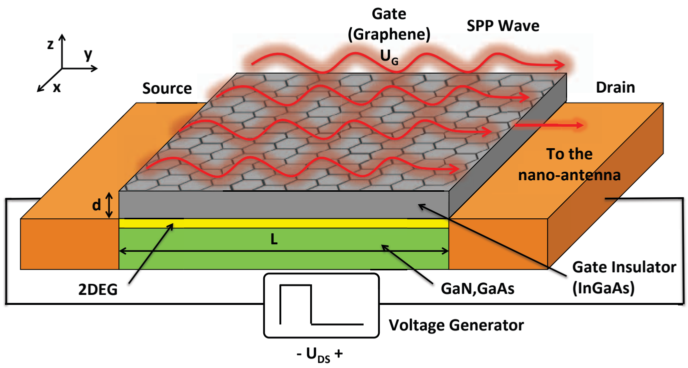



Fig. 2. Plasmonic nano-transmitter.

based plasmonic nano-transceiver for ultra-broadband wireless communication in the Terahertz Band. The nano-transceiver exploits the behavior of SPP waves in graphene to enhance the performance of HEMT-based signal generators and detectors at room temperature. The working principle of this design is based on the fact that, once a plasma wave is excited in the HEMT by means of electric pumping, this is wirelessly coupled to the graphene-based gate, thus creating a SPP wave. The advantageous SPP wave propagation properties of graphene allow the generation of the necessary signals to drive a plasmonic nano-antenna at Terahertz Band frequencies and at room temperature. In addition, the use of graphene as the medium in which the SPP wave propagates eases the integration of the nano-transceiver and the nano-antenna and can potentially minimize the interconnection losses with the rest of the components in the device.

The main contributions of this paper are summarized as follows. First, we define the conceptual plasmonic nano-transceiver architecture for Terahertz Band communication and describe its functioning in transmission and in reception. The details of the proposed architecture are given in Sec. II. We then focus on the transmitter and develop an analytical model for its frequency response. For this, we take into account the hydrodynamic equations that describe the generation of a plasma wave when the HEMT is electrically biased, the dynamic complex conductivity of graphene, and Maxwell's equations. Our analysis and numerical results are provided in Sec. III. Finally, we conclude the paper in Sec. IV.

## II. Plasmonic Nano-transceiver

In this section, we describe the proposed nano-transceiver architecture and explain its fundamental working principle in transmission and in reception.

### A. Nano-transceiver Architecture

The nano-transceiver architecture is shown in Fig. 1. The nano-transmitter is composed by two blocks, namely, the electric signal generator and the plasmonic transmitter. The *electric signal generator* modulates an electric signal according to the bit-stream that needs to be transmitted. This signal is then injected to the *plasmonic nano-transmitter*, which will convert the signal into a modulated SPP wave. The SPP wave is then radiated by a plasmonic nano-antenna [5], which converts the SPP wave into a propagating electromagnetic (EM) wave.

The propagating EM wave will eventually reach the receiver's nano-antenna, which will detect and convert the EM wave into a SPP wave. The nano-receiver is also composed by two blocks, namely, the plasmonic receiver and the electric signal detector. The *plasmonic nano-receiver* converts the SPP wave into an electric signal, which will then be detected and demodulated by the *signal detector*.

### B. Plasmonic Transmitter

The plasmonic transmitter (Fig. 2) consists of a HEMT built with a III-V semiconductor and a graphene-based gate [15] (a single layer graphene sheet is considered at this time, but a similar analysis could be done for multi-layer graphene). When a positive voltage is applied between the drain and the source of the HEMT, $U_{DS} > 0$, electrons are accelerated from the source to the drain. As first described in [16], [17] and experimentally shown in several works [12], [13], [14], electrons moving in the HEMT channel create a plasma wave through the Dyakonov-Shur instability. For a channel length in the order of a hundred nanometers, the plasma wave in the 2D electron gas (2DEG) resonates in the Terahertz Band. This holds as long as the voltage at the gate $U_G$ is above the threshold voltage of the HEMT, $U_G > U_T$.

Contrary to existing Terahertz Band sources, in our proposed design, the plasma wave is not directly radiated, but used to induce a propagating SPP wave at the interface with the graphene layer. The oscillating image charge created at the graphene-semiconductor interface in response to the confined plasma wave oscillation in the 2DEG results in a coupled oscillating charge distribution at or near the frequency at which the system is driven [18]. Due to the complex conductivity of graphene at Terahertz Band frequencies, this global oscillation of charge in the graphene-semiconductor interface results into a SPP wave [19], [20]. The propagation constant of the SPP wave, which can be tuned by modifying the chemical potential of the graphene layer, determines the SPP wave propagation length and confinement factor. Finally, the SPP wave can be used to excite a graphene-based plasmonic nano-antenna.

Note that this design is different from recent architectures in [14], [21], [22], in which graphene is directly used as

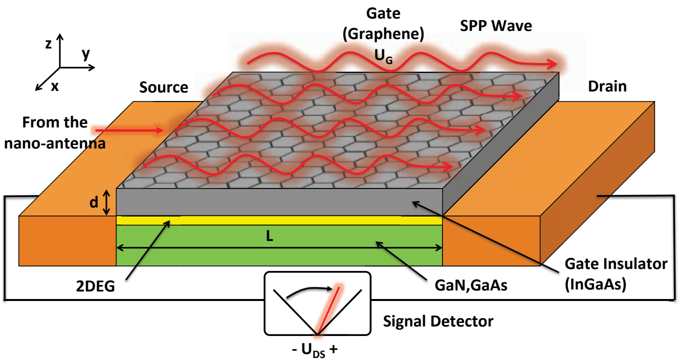



Fig. 3. Plasmonic nano-receiver.

the active element of a FET transistor but requires of optical pumping to operate. In addition, we utilize graphene and not a noble metal such as gold or silver, as good SPP wave propagation cannot be achieved in the Terahertz Band with these materials, but usually only at much higher frequencies [23].

### C. Plasmonic Receiver

Reciprocally, the same HEMT architecture can be used in reception (Fig. 3). The injection of SPP waves in the graphene-covered channel of a HEMT, for example from a graphene-based plasmonic nano-antenna, results into a coupled plasma wave in the 2DEG. The movement of electrons effectively creates a voltage between the drain and the source, $U_{DS} > 0$, provided that $U_G > U_T$. Recent works show how HEMT-based plasmonic detectors provide excellent sensitivities specially at very low temperatures. However, at room temperature, the performance decreases.

The response of the nano-receiver to the SPP wave at Terahertz Band frequencies can be enhanced at room temperature by using graphene. On the one hand, the use of the same nanomaterial as in the nano-antenna simplifies the interconnection of the two nano-components and minimizes the losses due to impedance mismatch. On the other hand, the excellent sensing capabilities of graphene due to the fact that all its atoms are exposed to the medium, results in a much lower sensitivity. In addition, as we mentioned before, the response of the graphene layer can be easily tuned by means of material doping until finding the optimal working conditions for the entire graphene-based heterostructure.

## III. Analytical Modeling and Numerical Results

The analysis of the performance of the proposed nano-transceiver requires us to jointly model the behavior of electrons in the HEMT when electrically biased and the behavior of SPP waves in the graphene layer. In the remaining of this paper, we focus on the plasmonic transmitter. A similar analysis can be conducted for the plasmonic receiver, which will be included in an extended version of this work.

### A. Plasma Wave Excitation

The plasma wave behavior in the HEMT channel is described by the extended Dyakonov-Shur model [16], [17]. The local electron velocity $v$, the electric potential $U$ and the local electron density $n$ in the HEMT channel are formulated by the hydrodynamic equations, composed of the Euler equation:

$$\frac{\partial v(y,t)}{\partial t} + v(y,t)\left(\frac{\partial v(y,t)}{\partial y}\right) + \frac{v(y,t)}{\tau} + \frac{e}{m^*}\frac{\partial U(y,t)}{\partial y} = 0, \quad (1)$$

and the continuity equation:

$$\begin{aligned} e\frac{\partial n(y,t)}{\partial t} - \frac{\partial j(y,t)}{\partial y} &= 0, \\ \frac{\partial n(y,t)}{\partial t} + \frac{\partial n(y,t)\, v(y,t)}{\partial y} &= 0, \\ \frac{\partial U(y,t)}{\partial t} + \frac{\partial U(y,t)\, v(y,t)}{\partial y} &= 0, \end{aligned} \quad (2)$$

where $\tau$ is the plasmon relaxation time, $e$ is the electric charge, and $m^*$ is the electron effective mass, $U(x,t) = U_G(y,t) - U_T$ is the gate-to-channel voltage, and $j(y,t) = -en(y,t)\,v(y,t)$ is the electric current density in the HEMT channel. The last equality in (2) is valid under the gradual channel approximation, which considers that the characteristic scale of the potential variation in the channel is much greater than the gate-to-channel separation and for which we can write

$$n(y,t) = C\frac{U(y,t)}{e} = \frac{\varepsilon_0\varepsilon_r^1}{d}\frac{U(y,t)}{e}, \quad (3)$$

where $n$ is the local electron density, $C$ is the gate capacitance per unit area, $U$ is the gate-to-channel voltage, $e$ is the electronic charge, $\varepsilon_0$ and $\varepsilon_{r1}$ are the permittivity of vacuum and the relative permittivity of the gate insulator, respectively, and $d$ is the gate insulator thickness. We consider that the source and the drain are connected to a current source and the gate and the source are connected to a fixed voltage source.

The plasma wave vector $k_p$ can be found by assuming that the electron velocity $v$ has the form $v(y,t) = v_0 + v_1(y)\exp(-\mathrm{i}\omega t)$, where $v_0$ is constant and $\omega = 2\pi f$ is the angular frequency, and the electric potential across the channel is $U(y,t) = U_0 + U_1(y)\exp(-\mathrm{i}\omega t)$, where $U_0$ is a constant voltage at the gate. By solving the system of equations given by (1) and (2) with the boundary conditions imposed by aforementioned voltage and current sources, i.e., $U_1(y=0) = 0$ and $\Delta j(y=L) = 0$, the plasma wave vector is given by

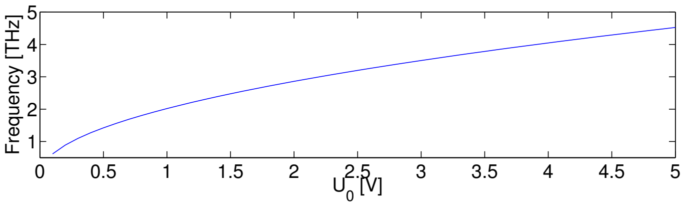
$$k_p = \frac{\omega}{v_p}, \quad (4)$$

$$\omega = \omega' + \mathrm{i}\omega'', \quad (5)$$

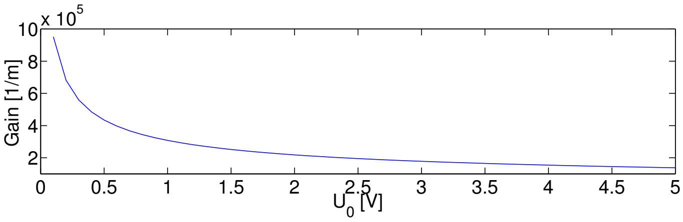
$$\omega' = \frac{\left|v_p^2 - v_0^2\right|}{2Lv_p}\pi, \qquad \omega'' = \frac{v_p^2 - v_0^2}{2Lv_p}\ln\left|\frac{v_p + v_0}{v_p - v_0}\right|, \quad (6)$$

$$v_p = \left(\frac{eU_o}{m^*}\right)^2, \quad (7)$$

where $v_p$ is the plasma wave velocity, $L$ is the HEMT channel length and the rest of terms have already been defined. From (6), it is clear that if $0 < v_0 < v_p$, $w'' > 0$ and, thus, there is a gain that results from the so-called Dyakonov-Shur instability. In Fig. 4, the plasma wave resonant frequency $f = \omega'/2\pi$ and the gain $g = \omega''/v_p$ are plotted as functions of the gate voltage $U_0$, when the the HEMT channel length




(a)




(b)

Fig. 4. Plasma wave propagation properties.

$L = 200$ nm and the gate insulator is InGaAs, with $\varepsilon_{r1} = 13.1$, $m^* = 0.067m_e$, where $m_e$ is the electron mass, thickness $d = 30$ nm and electron drift velocity $v_0 = 10^5$ m/s. The plasma wave resonates in the Terahertz Band.

### B. Surface Plasmon Polariton Wave Excitation

The coupled oscillations of charge at the graphene-semiconductor interface result into a propagating SPP wave. In the absence of a graphene layer, when an ideal metallic gate is used, the emission of a plasma wave to free space results usually in a low efficiency due to the mismatch between the plasma wave propagation constant in the 2DEG channel, and the EM wave propagation constant in free space. To improve this limitations, diverse structures such as gate grating [24], [14] can be used to enhance the plasmonic emission.

Instead of this, we use graphene to propagate a Transverse Magnetic (TM) SPP wave towards a more suited radiating structure, such as a graphene-based plasmonic nano-antennas. The dynamic complex SPP wave vector $k_{spp} = \omega/v_{spp}$ is obtained by solving the dispersion equation:

$$\frac{\varepsilon_r^2}{\sqrt{k_{spp}^2 - \frac{\varepsilon_r^2\omega^2}{c_0^2}}} + \frac{\varepsilon_r^1}{\sqrt{k_{spp}^2 - \frac{\varepsilon_r^1\omega^2}{c_0^2}}} = -\mathrm{i}\frac{\sigma_y}{\omega\varepsilon_0}, \qquad (8)$$

where $\varepsilon_r^n$ is the relative permittivity of medium $n$ ($n = 1$ below the gate, $n = 2$ above the gate), $c_0$ is the speed of light in vacuum, and $\sigma_y$ stands for the conductivity of graphene along the $y$ axis. Equation (8) is obtained by jointly solving the Maxwell's equations for the electric field $\vec{E}$ and the magnetic field $\vec{H}$ at the graphene-semiconductor interface, with the boundary condition at $z = d$

$$H_x\bigg|_{z=d-} - H_x\bigg|_{z=d+} = J_y = \sigma_y E_y, \qquad (9)$$

where $J_y$ is the $y$ component of the current induced at the graphene-semiconductor interface by the plasma wave in the HEMT channel. A closed-form solution for $k_{spp}$ can only be obtained when considering a single isolated graphene sheet surrounded by air ($\epsilon_1^r = \epsilon_2^r = 1$), which is not our case. For this, only numerical results are provided.

The dynamic complex conductivity of graphene $\sigma$ in (8) depends on the chemical potential, temperature and size of the graphene layer. In an attempt to remain general, instead of using the conductivity model for infinitely large graphene sheets, we utilize the model developed in [5], which takes into account the impact of lateral confinement. For a semi-finite graphene sheet, the dynamic complex conductivity along the $y$ direction of a semi-finite graphene sheet is given by

$$\sigma_y(f) = \mathrm{i}\frac{\hbar e^2}{S}\sum_{s,s'}\sum_{n,m}\int_k \frac{\left(n_F(\varepsilon_m^{s'}) - n_F(\varepsilon_n^s)\right)}{(\varepsilon_n^s - \varepsilon_m^{s'})} \frac{\left|\langle\phi_m^{s'}|v_\alpha|\phi_n^s\rangle\right|^2}{(\varepsilon_n^s - \varepsilon_m^{s'} + hf - \mathrm{i}\nu_G)}dk, \qquad (10)$$

where $f$ stands for frequency, $\hbar$ is the reduced Planck constant, $e$ is the electron charge, $S$ is the area of the reference unit structure, $\{s, s'\}$ stand for band indexes, $\{n, m\}$ refer to the sub-bands indexes, $k$ is the wave vector parallel to the graphene edge, $n_F$ is the Fermi-Dirac distribution given by

$$n_F(\varepsilon) = \frac{1}{1 + e^{\frac{\varepsilon - u_0}{k_B T}}}, \qquad (11)$$

where $u_0$ is the chemical potential in eV, $k_B$ is the Boltzmann constant in eV/K, and $T$ stands for the temperature in K. $\langle\phi_m^{s'}|v_\alpha|\phi_n^s\rangle$ is the matrix element of the $\alpha$ component of the velocity operator for the transition from the energy state $\{s, n\}$ to the energy state $\{s', m\}$. The parameter $\nu_G$ in (10) refers to the inverse of the relaxation time in graphene.

We can then analyze the excitation of SPP waves by combining (10) with (8) and solving the system at the plasma wave frequency $f$ given by (5). In Fig. 5(a), the real part of the SPP wave vector $\Re\{k_{spp}\}$ is plotted as a function of the excitation frequency $f$, obtained from the plasma wave vector $k_p$ given by (4). These results are obtained for a square graphene patch with 200 nm side, with an electron relaxation time $\tau = h/\nu = 0.2$ ps, which is a rather conservative value, at $T = 300$ K. The values of $k_{spp}$ are normalized by the wave vector in the vacuum, $k_0$. For this plasma wave resonant frequency and potential, the graphene sheet supports the propagation of SPP waves with a relatively high confinement factor ranging from $k_{spp}/k_0 = 5$ at 1 THz up to 20 at 4.5 THz. In Fig. 5(b), the inverse of the imaginary part of the SPP wave propagation factor is illustrated as a function of the excitation frequency. It can be seen that the SPP wave propagation length is up to a few SPP wavelengths, which should be enough to reach the radiating element, e.g., the plasmonic nano-antenna. These results support the concept of using a plasma wave source to trigger a SPP wave on a graphene sheet. Several refinements are needed to develop a more complete model. For example, the impact of electron thermalization on the SPP wave dynamics at THz frequencies needs to be taken into account, at least for high fields [25]. In

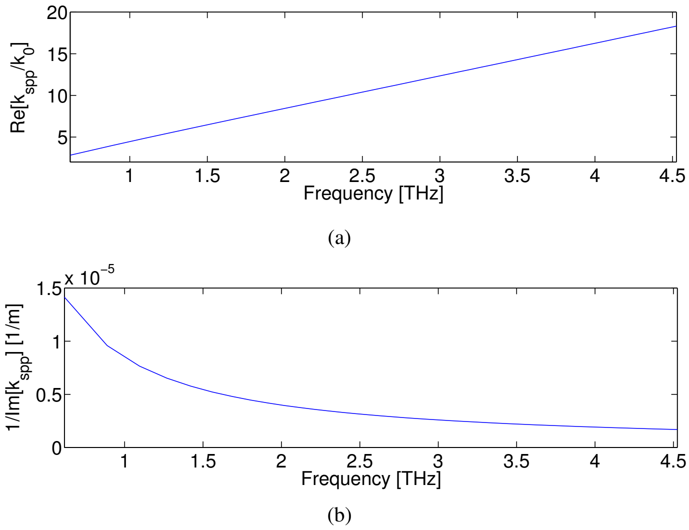



Fig. 5. Surface Plasmon Polariton wave propagation properties.

addition, more complex designs that maximize the response of the plasma wave source and the coupling with the SPP wave in graphene need to be pursued.

## IV. Conclusions

In this paper, we have proposed a plasmonic nano-transceiver for wireless communication in the Terahertz Band (0.1-10 THz). The nano-transceiver is based on a HEMT built with a III-V semiconductor and enhanced with graphene. The frequency response of the nano-transceiver in transmission has been analytically modeled by jointly taking into account the hydrodynamic equations governing the generation of the plasma waves in the HEMT, the dynamic complex conductivity of graphene and the Maxwell's equations. Our preliminary results support the concept of utilizing a plasma wave source as a mechanism to excite the necessary plasmonic current to drive a plasmonic nano-antenna at Terahertz Band frequencies. Ultimately, the use of the same nanomaterial as in the envisioned plasmonic nano-antennas facilitates the transceiver-antenna integration and is expected to minimize the interconnection losses between them.

## Acknowledgement

This work was supported by the US National Science Foundation (NSF) under Grant No. CCF-1349828.

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