Design and analysis of MIMO system for THz communication using terahertz patch antenna array based on photonic crystals with graphene

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Received: 5 July 2022 / Accepted: 6 August 2022
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Abstract
In this paper, a novel multiple input/multiple output (MIMO) antenna system with a graphene-based patch antenna array for THz communications channel capacity enhancement has been proposed and investigated. Systematic analysis has been conducted on the graphene load conductivity by determining the operating modes related to its chemical potential. Further, the projected MIMO antenna arrays have been designed with three different approaches such as homogeneous, photonic crystals, and optimized photonic crystals. The targeted MIMO antenna arrays have been compared with their radiation characteristics such as return loss, bandwidth, and gain. The obtained results in CST simulations of the proposed graphene-based 1×2 patch antenna array using the optimized photonic crystals substrate exhibited excellent performance improvements as compared to the homogeneous substrate and the photonic crystals substrate around 0.65 THz, which achieved a peak gain of 11.80 dB and broad bandwidth greater than 614 GHz. Next, The 2×2 MIMO system scenario was studied and analyzed using the mentioned targeted MIMO antenna arrays by calculating the total path loss and the channel capacity. The obtained results showed that the proposed 2×2 MIMO system with the MIMO antenna array based on the optimized photonic crystals substrate achieved the highest capacity and the lowest total loss compared to a simple MIMO antenna array based on a homogeneous substrate. The capacity was calculated as 23.64 bit/s/Hz, and this was a remarkable enhancement compared with previously reported studies. In addition, this capacity was investigated further for different system configurations and different spacings between the transmission and receiver antennas.

Keywords Microstrip patch antenna array · MIMO · CST · Photonic crystal · THz band · Channel capacity · Radiation characteristic · Graphene
1 Introduction

Over the last decade, the THz band was envisioned as the key technology, which is identified as the spectral band that spans frequencies between 0.1 THz and 10 THz (Piesiewicz et al. 2007). The THz band offers a very broad bandwidth that can reach hundreds of GHz in order to fulfill the increasing demand for a faster high data transmission rate in a communication link (Song and Nagatsuma 2011). High capacity channels have become a very important trend for keeping pace with the rapid growth of numerous wireless technologies in which the terahertz channel has distinct characteristics compared to the channel of lower band systems (Boronin et al. 2014). Unfortunately, the transmission path loss, as well as molecular absorption loss are regarded as the main issue in the THz band, due to the high atmospheric attenuation (Schneider et al. 2012). To compensate for the impact of these losses at THz frequencies while supporting high data rates, antennas should exhibit both high gain at the radiation angle with the lowest loss and wide bandwidth (Jha and Singh 2013). Besides the mentioned losses, the scattering and reflection of waves behaviors are also different from those in the GHz band (Jansen et al. 2011; Piesiewicz et al. 2007; Mujumdar et al. 2004). The surfaces of indoor objects at THz are regarded as rough surfaces instead of smooth surfaces because the traveling wavelength is comparable to the roughness of indoor surfaces such as plaster or wallpaper (Whitman et al. 2016). Furthermore, the environments change quite slowly for indoor communications due to slowly moving objects compared to terahertz waves through a certain time window. So, it is assumed that moving objects can be counted as static objects between the transmission antenna and the receiver antenna (Temmar et al. 2021). In most situations, the channel may be influenced by fading, therefore, these distinctive features guide new models to characterize the THz channel. The use of multiple-input multiple-output (MIMO) antenna methods may minimize signal fading concerns in wireless networks, thereby increasing system capacity. However, the MIMO systems have main obstacles that include limited area, antenna size, and spacing (Tse and Viswanath 2005; Alharbi and Sorathiya 2022). Therefore, graphene-based directional antennas using the photonic crystals substrate can be promising candidates to overcome such limitations (Temmar et al. 2021; Bala and Marwaha 2015; Kushwaha and Karuppanan 2020). Graphene is an allotrope of carbon that consists of a single layer of atoms arranged in a two-dimensional honeycomb lattice nanostructure which initially was introduced in 2004 (Geim and Novoselov 2010). Graphene has outstanding physicochemical properties such as high thermal and electrical conductivity, high density, good biocompatibility, low electricity consumption, and high resistance, graphene is approximately 200 times stronger than steel (Ghosh et al. 2019; Falkovsky 2008). Due to the great properties mentioned above, graphene has applicability in numerous fields like medical sensors (Gan and Hu 2011), biosensing (Pumera 2011), filters and absorbers (Cheng et al. 2020). In addition, graphene has been used in THz antennas to improve their radiation characteristics by changing the electrostatic voltage bias (Perruisseau-Carrier 2012; Bala and Marwaha 2016; Dragoman et al. 2010). In THz communications, there are various types of antenna designs that are needed to adapt to the THz channel. Among them, Yagi-Uda (Han et al. 2010), bow tie (Maraghechi and Elezzabi 2011), on-chip antenna (Alibakhshikenari et al. 2020), horn antenna (Wu et al. 2012), MEMS antenna (Guo et al. 2016), Leaky wave antenna (Gerboukha et al. 2020) and Lens antenna (Wu et al. 2019). However, a complicated design procedure and a larger size are required for these mentioned antennas to function. For this aim, the microstrip patch antennas are becoming more ubiquitous as planar technology, because of their various advantages, including low cost,
light weight, small size, design simplicity, and compatibility with integrated circuit technology (Shamim et al. 2021a, 2021b). Despite their numerous advantages, the conventional patch antenna suffers from a number of drawbacks, such as narrow bandwidth, low gain, poor radiation performance, and surface wave excitation due to the substrate’s high permittivity and comparatively huge thickness (Tiang et al. 2011; Alam et al. 2012; Britto et al. 2021).

These drawbacks can be overcome by introducing the concept called photonic crystal (PhC). A photonic band gap material, also known as a photonic crystal, is an artificial material made of periodic implants within a surrounding medium. The photonic crystal is a new class of periodic dielectric structures that has been developed in which electromagnetic wave propagation in any direction is completely forbidden for all frequencies within a stop band, these structures have promising applications such as transmission line for biosensing, optical gate, optical and microwave cloak (Turduev et al. 2017; Semouchkina et al. 2016). Moreover, it is reported that these structures have been used in THz antenna as a substrate for gain and radiation characteristics enhancement (Benlakehal et al. 2022; Temmar et al. 2020; Fernandes et al. 2003; Lin et al. 2011; Hocini et al. 2019). There are different types of photonic crystals such as 1D, 2D, or 3D structures, depending on their periodic arrangements. Two-dimensional (2D) photonic crystals have gained a lot of interest from many researchers in recent years, because they are much easier to fabricate compared to three-dimensional (3D) photonic crystals (Qi et al. 2004; Temmar et al. 2019; Vlasov et al. 2001), furthermore, characterizing photonic crystal structures using a purely analytical approach is generally difficult because of their complexity. Therefore, full-wave simulators such as CST Microwave Studio, which is based on the finite integration technique have been used to analyze microstrip patch antennas based on the photonic crystals substrate (Agi et al. 1999; Chow et al. 2000; Benisty et al. 1999). In this paper, a novel multiple input/multiple output (MIMO) indoor communication system was developed using a 1x2 microstrip patch antenna array based on the optimized photonic crystals substrate with a graphene load in order to enlarge the channel capacity. The proposed MIMO antenna array was designed around 0.65 THz to offer a high gain to overcome the path losses. This paper is organized as follows: in Sect. 2, the design and the performance of the proposed antenna array based on the homogeneous, photonic crystals and optimized photonic crystals substrates are explained and investigated. In Sect. 3, we describe the interesting characteristics of the graphene load. In Sect. 4, we investigate the radiation characteristics of our MIMO antenna array design based on the homogeneous, photonic crystals and optimized photonic crystals substrates with the graphene load, then we explain the application of the proposed MIMO antenna array in a normal indoor communication environment by calculating the total path loss and the channel capacity for different system configurations and spacings. Finally, we give our conclusions in Sect. 5.

2 Antenna array design based on the photonic crystals

In this section, three rectangular 1x2 microstrip patch antenna arrays based on three different substrates including the homogeneous, photonic crystals, and optimized photonic crystals substrates are designed and analyzed in the frequency range of 0.5–0.9 THz. The three antenna array designs were investigated using the CST simulator, which is based on the finite integration technique (Studio 2017). Antenna array 0, namely the conventional antenna array based on the homogeneous substrate, is designed and simulated for
comparison purposes. Antenna array 1 structure consists of two symmetrical patch elements which are fed by the parallel feeding technique (Balanis 1992) and mounted on a substrate that employs photonic crystals. The photonic crystal structure is made of air cylinders embedded in a dielectric constant of 2.91 and a loss tangent of 0.0001 with a thickness of \( h \). The air holes have a lattice constant and a radius of 127.95 \( \mu m \) and 15 \( \mu m \), respectively. Hence, the dimensions of the square unit cell are 127.95 \( \times \) 127.95 \( \mu m \) as shown in Fig. 1. The width \( W_p \) and length \( L_p \) of the patch can be found based on the equations in (Benlakehal et al. 2022). The feed network is designed to distribute the power in equal parts to achieve a 50 \( \Omega \) impedance. Hence, the width of the feed network \( W \) is given by (Kushwaha and Karuppanan 2020):

\[
W = \frac{0.8}{5.98h} \exp \left[ \frac{Z_c}{87\sqrt{\epsilon_r + 1.41}} \right]
\]  

(1)

where, \( Z_c \) is the impedance of a feed line, \( h \), \( \epsilon_r \) are the thickness and the dielectric constant of the substrate material, respectively. The dimensions of antenna array 0 and antenna array 1 are presented in Table 1.

Antenna array 2 is designed based on antenna array 1 structure, however, the air cylinders in the substrate were optimized and divided into several sets of air holes, each set of air holes had a different radius. Hence, antenna array 2 is designed with teen sets of air holes that are vertically different. The radii of the air holes are \( R_1=50 \mu m \), \( R_2=30 \mu m \), \( R_3=5 \mu m \), \( R_4=25 \mu m \), \( R_5=15 \mu m \), \( R_6=10 \mu m \), \( R_7=26 \mu m \), \( R_8=15 \mu m \), \( R_9=46 \mu m \), and \( R_{10}=30.5 \mu m \). Finally, the structures of antenna array 0, antenna array 1, and antenna array 2 based on the homogeneous, photonic crystals and optimized photonic crystals substrates, respectively are shown in Fig. 2.

Figure 3 presents the return loss of the described antenna arrays in the frequency range of 0.5–0.9 THz, clearly showing that antenna array 2 based on the optimized photonic crystals offers a return loss of -32.27 dB and exhibits a wider bandwidth greater than 374 GHz at a resonance frequency of 0.625 THz. Then, antenna array 1 based on photonic crystals offers a return loss of -28.35 dB and a bandwidth of 260 GHz at a resonance frequency of 0.619 THz compared with antenna array 0 based on the homogeneous substrate that offers
Table 1 Parameter values for antenna array 0 based on a homogeneous substrate and antenna array 1 based on the photonic crystals substrate

| Parameter                      | Value (μm) |
|--------------------------------|------------|
| Antenna array 0               | Antenna array 1 |
| Patch width (Wp)              | 165        | 360        |
| Patch length (Lp)             | 71         | 220        |
| Distance between patches (d)  | 464.40     | 584.80     |
| Substrate thickness (h)       | 80         |            |
| Ground plane thickness (t)    | 4.85       |            |
| Cylinder radius (R)           | 15         |            |
| Lattice constant (a)          | 127.95     |            |
| Substrate width (Ws)          | 10 × a     |            |
| Substrate length (Ls)         | 7 × a      |            |
| Feed line width (W)           | 109.23     |            |
| Feed line width (Wf)          | 6.6        |            |
| Feed line length (L)          | 204.47     |            |
| Feed line length (Lf)         | 142.98     |            |

(a) Antenna array 0. (b) Antenna array 1. (c) Antenna array 2.

Fig. 2 The geometry of the designed antenna arrays
a return loss of -27.1 dB and a bandwidth of 164 GHz at a resonance frequency of 0.657 THz.

Figure 4 displays the gain of the designed antenna arrays in the frequency range of 0.55–0.75 THz. At their resonant frequencies, it is observed that antenna array 2 has yielded the maximum gain with the value of 11.31 dB, then antenna array 1 achieved 10.95 dB, whereas the conventional antenna array achieved a gain of 9.25 dB.

Figure 5 shows the radiation pattern for the designed antenna arrays at their respective resonating frequencies. The maximum radiation in the pattern of antenna array 2 occurs at $\theta=27^\circ$ with the maximum directivity of 11.60 dBi. Whereas, antenna array 1 and antenna array 0 have the maximum radiation in the pattern at $\theta=29^\circ$, $\theta=26^\circ$ with the maximum directivity of 11.30 dBi, 9.46 dBi, respectively. In addition, the side lobe was reduced after employing the photonic crystals compared to a homogeneous substrate. Thus, considering the obtained results such as return loss, bandwidth, gain, and directivity, there were
remarkable enhancements in the conventional antenna array performance after implement-
ing the photonic crystals, however, it could be worth interesting to observe that with the vertical change in the air cylinder holes of the photonic crystals, an extra performance is provided as found in antenna array 2. The enhancements in the antenna array performance is due to the suppression of the excited surface waves transmitted along the substrate. The surface waves absorbed by the conventional antenna array are much more than that absorbed by the PBG substrate which result in small bandwidth and low gain, therefore, the enlargement of the non-transmission frequency band made by the photonic crystal structures reduced the substrate absorption and thereby enhanced the bandwidth and the gain of the antenna array (Li et al. 2012; Benlakehal et al. 2022).

3 Properties of graphene

Graphene is an allotrope of carbon composed of a single layer of atoms arranged in a two-
dimensional honeycomb lattice, which can conduct better electricity and heat incredibility than copper. Its total surface conductivity $\sigma(\omega, \mu_c, \tau, T)$ can be expressed by Kubo’s equations (Hanson 2013):

$$\sigma(\omega, \mu_c, \tau, T) = \frac{e^2(\omega - 2j\tau)}{\pi \hbar^2} \times \left[ \frac{1}{(\omega - j2\tau)^2} \int_0^\infty e\left(\frac{\delta f_d(\epsilon)}{\delta \epsilon} - \frac{\delta f_d(-\epsilon)}{\delta \epsilon}\right) d\epsilon - \int_0^\infty \frac{f_d(-\epsilon) - f_d(\epsilon)}{(\omega - j2\tau)^2 - 4(\frac{\epsilon}{\tau})^2} d\epsilon \right]$$

(2)

where $\omega=$the angular frequency, $\mu_c=$chemical potential, $\tau=$relaxation time, $T=$temperature, $K_B=$Boltzmann’s constant, $h=$reduced Planck’s constant, $h=$ normal Planck’s constants, and the Fermi-Dirac $f_d(\epsilon)$ distribution is represented as (Yao et al. 2013):

$$f_d(\epsilon) = \left(e^{\frac{\epsilon - \mu_c}{k_B T}} + 1\right)^{-1}$$

(3)

Fig. 5 The radiation pattern of the designed antenna arrays at their resonant frequencies
For the present work, $T=300\,\text{K}$, $e=1.610^{-19}\,\text{C}$, $\tau=1\,\text{ps}$, and $\mu_c$ is changed from 0 to 1.5 eV to analyze the conductivity behavior. In addition, graphene carrier density $n_s$ is described as follows (Esfandiyari et al. 2019):

$$n_s = \frac{2}{\pi h^2 V_f^2} \int_0^\infty e^{[f_d(e) - f_d(e + 2\mu_c)]} de$$  \hspace{1cm} (4)

where $V_f$ is the Fermi velocity. The chemical potential $\mu_c$ is controlled by the carrier density $n_s$. Hence, graphene conductivity can be easily inhibited by varying the chemical potential $\mu_c$, which can be controlled by the carrier density $n_s$. The chemical potential $\mu_c$ can be changed via chemical doping or electrostatically biasing it. When $\mu_c = 0\,\text{eV}$, graphene conductivity is almost 1000 times less than the conditions of $\mu_c = 1.5\,\text{eV}$, hence graphene has two modes, high resistance mode when $\mu_c = 0\,\text{eV}$ and low resistance mode when $\mu_c = 1.5\,\text{eV}$ (Hanson 2008). The surface impedance of graphene for different chemical potentials is shown in Fig. 6. It can be clearly seen that the real impedance of graphene is decreased by increasing the chemical potential $\mu_c$ in the frequency range of 0.4–1.1 THz.

4 MIMO system design

4.1 Antenna array design and analysis with a graphene load

In Sect. 2, we have seen that the antenna array structure based on the optimized photonic crystals substrate offered an extra performance compared to the antenna array based on the homogeneous and the photonic crystals substrates. In this section, we designed and developed three different MIMO antenna arrays based on antenna array 0, antenna array 1 and antenna array 2 structures. The MIMO antenna array structure is made by a copy of the antenna array structure, which is fed by another port where each port was fed separately, shifted by a distance of 140 $\mu\text{m}$ and rotated around its center. At each side of the radiator patches, a graphene load is added which was modeled using a volumetric approach with an acceptable thickness for the graphene monolayer. The graphene load had a width $W_g$ of

![Graphene Properties](image)

**Fig. 6** Properties of graphene
42.36 \, \mu m, a length similar to the length of the patch of \( L_p \) 220 \, \mu m and thickness of 0.34 nm which was compatible with the chemical potential tuning of graphene. A change in the electrical conductivity of graphene leads to an increase in the gain of the MIMO antenna array compared to a simple MIMO antenna array. Therefore, the first MIMO antenna array was based on a homogeneous substrate which is labeled as MIMO antenna array 0, the second MIMO antenna array was based on the periodic photonic crystals with \( \mu_c = 1.5 \, \text{ev} \) which is labeled as MIMO antenna array 1 and the third MIMO antenna array was based on the optimized photonic crystals with \( \mu_c = 1.5 \, \text{ev} \) which is labeled as MIMO antenna array 2 as shown in Fig. 7. The CST microwave studio software has been used to calculate the MIMO antenna array features. The scattering parameters \( S_{11} \), \( S_{21} \), \( S_{12} \), and \( S_{22} \) were extracted for the MIMO antenna array based on the homogeneous substrate and for the MIMO antenna array based on the photonic crystals with optimized photonic crystals substrates, where the utilized chemical potential was 1.5 ev as shown in Fig. 8. The resonance frequencies of the designed MIMO antenna arrays were observed at around 0.65 THz. MIMO antenna array 0 resonated at the frequency of 0.66 THz with a return loss of −25.27 dB. Whereas, MIMO antenna arrays 1 and 2 resonated at the frequencies of 0.631 THz and 0.638 THz, respectively with the return losses of −40.68 dB and −41.30 dB, respectively. The −10 dB bandwidths were 174, 300, and greater than 614 GHz for MIMO antenna array 0, MIMO antenna array 1, and MIMO antenna array 2, respectively. Thus, employing the periodic photonic crystals and the optimized photonic crystals with a graphene load as seen in
MIMO antenna arrays 1 and 2, respectively enlarged the bandwidth compared with MIMO antenna array 0, which was designed based on the homogeneous substrate, which is very important for high data transmission rates based on Shannon theorem (Huang and Wang 2011). Fig. 9 displays the gain performance of the designed MIMO antenna arrays in the frequency range of 0.55–0.75 THz. Clearly, the gain was enhanced when the graphene load operated in the low resistance mode for both MIMO antenna arrays 1 and 2 due to the suppression of surface waves by the photonic crystals substrate compared to the conventional MIMO antenna array. Therefore, at their resonating frequencies, MIMO antenna array 2 achieved the maximum gain with the value of 11.80 dB, whereas MIMO antenna arrays 1 and 0 achieved 11.48 dB and 9.44 dB, respectively. The radiation patterns of the designed MIMO antenna arrays are investigated with the corresponding resonance frequencies which can be revealed in Fig. 10. The directivity of MIMO antenna array 0 was maximized at the incidence angles $\theta$ of $27^\circ$ and $-27^\circ$ for port 1 and port 2, respectively with the value of 9.84 dBi at the resonance frequency of 0.66 THz. Whereas, the maximum directivity of MIMO antenna arrays 1 and 2 was achieved at the incidence angles $\theta$ of $30^\circ$ and $-30^\circ$ for port 1 and port 2, respectively with the values of 12.40 dBi and 12.80 dBi, respectively at resonating frequencies of 0.631 THz and 0.638 THz, respectively. The 3D far field radiation pattern for MIMO antenna array 2 is shown in Fig. 11. The radiation characteristics such as return loss and gain of the designed MIMO antenna array based on the optimized photonic crystals were investigated by changing the different chemical potentials ($\mu_c=0$ eV, 0.7 eV, 1 eV, 1.2 eV), then compared them to the case of $\mu_c=1.5$ ev. The results are presented in Fig. 12 which confirm the previously obtained conclusions. The gain was slightly ameliorated by increasing the chemical potential of the graphene load from 0 to 1.5 ev, which corresponded to the low resistive mode of the graphene load, moreover, the introduction of the small graphene load widened the bandwidth.

4.2 Losses and terahertz channel capacity

Terahertz band communication is considered as a key wireless technology. The THz channel model has been studied and discussed in several recent works because of its promising
characteristics, alleviating the path loss limitations (Temmar et al. 2021; Esfandiyari et al. 2019; Han et al. 2014; Jornet and Akyildiz 2011; Xu et al. 2014). In order to get the capacity of the MIMO system, the total path loss in the THz band should be studied first. For the line of sight communication systems, losses are mainly due to free-space path loss which is contributed by two frequency-dependent terms: the spreading loss $A_{\text{spread}}$ and the molecular absorption loss $A_{\text{abs}}$. In addition to the mentioned losses, the reflection loss $A_{\text{ref}}$ which is due to the collision of waves with indoor rough surfaces. The surfaces of indoor objects, which can be considered as smooth surfaces at the GHz frequency, are now regarded as
rough surfaces at the THz frequency band. The formulas for the spreading loss, molecular absorption loss, and reflection loss are defined as follows (Xu et al. 2014; Benlakehal et al. 2022):

\[ A_{\text{spread}}(f, d) = 20 \log\left(\frac{4 \pi f d}{c}\right) \]  

\[ A_{\text{abs}} = k(f) d 10 \log_{10} e \]  

where \( A_{\text{spread}} \) is the spread loss in dB, \( f \) is the operating frequency, \( d \) is the traveled distance and \( c \) is the speed of light. \( A_{\text{abs}} \) is the molecular absorption loss in dB, \( K(f) \) is the medium absorption coefficient and equals the sum of weighted coefficients of each gas in the air. Since the total band is segmented into several transmission windows, the molecular absorption is very small and it can be ignored at the window around 0.65 THz. The roughness factor \( \rho \) is given as follows:

\[ \rho = e^{-\frac{g^2}{2}} \]

\[ g = \left( \frac{2 \pi \Delta (\cos(\theta_I) + \cos(\theta_O))}{\lambda} \right)^2 \]

where \( g \) represents the intensity of the surface variation, \( \Delta \) is the standard deviation coefficient of the surface roughness (88 \( \mu \)m for plaster), \( \theta_I \) and \( \theta_O \) are the angles of incidence and reflection, respectively.

The gain matrix \( H \) comprises the gain between the \( i \)th transmit antenna and the \( j \)th receive antenna which obtained from the following formula (Goldsmith 2005):

\[ h_{ij} = -A_{\text{spread}} - A_{\text{abs}} + \rho + G_T + G_R \]

where \( G_T \) and \( G_R \) are the transmitter and the receiver antenna gain at the angle of incidence \( \theta_I \) and the angle of reflection \( \theta_O \), respectively. These angles were calculated for the length.
of the radiation path $d_{ij}$ based on the scenario presented in Fig. 13 using the following formulas (Esfandiyari et al. 2019):

$$\frac{Sp_i}{\cos(\theta_i)} + \frac{Sp_{ij}}{\cos(\theta_O)} = d_{ij}$$

(10)

$$Sp_i \tan(\theta_{ii}) + Sp_{ij} \tan(\theta_{Oij}) = L_{ij}$$

(11)

where $Sp_i$ is the distance between the transmitter and the corresponding indoor wall, $Sp_{ij}$ is the distance between the receiver $j$ and indoor wall $i$, $L_{ij}$ is the horizontal distance between the transmitters and receivers and $d_{ij}$ is the length of the radiation path between the $ith$ transmit antenna and the $jth$ receive antenna. Whereas, $d_t$ and $d_r$ are the spacings between the transmitters and between the receivers, respectively.

Finally, for the channel computation, we consider a system with $M$ transmit antennas and $N$ receive antennas, and the channel can be represented as an $M \times N$ matrix. The time-invariant channel is described as:

$$y = Hx + w$$

(12)

where $x$ is the transmit signal, $y$ is the receive signal and $w$ is the white Gaussian noise. The capacity is given by maintaining singular values $\lambda_i$ for the gain matrix $H$ as follows (Goldsmith 2005):

$$C = \sum_{i=1}^{\text{min}} \log_2 \left( 1 + \frac{p_i \lambda_i^2}{N_0} \right) \frac{b}{s/Hz}$$

(13)

where $\text{min}$ is the rank of the matrix $H$, $p_i$ is the transmitting power from the $ith$ MIMO antenna array, $\lambda_i$ is the singular values of the matrix $H$ and $N_0$ is the noise power spectral density which is taken as 0.01 nW.

4.3 Results and discussion

Now, channel capacity will be investigated for the defined scenario given in Fig. 13. First, the total path loss that includes the spreading loss, molecular absorption loss, and reflection loss should be estimated. Therefore, It is important to have the main direction

Fig. 13 A scenario based on the MIMO antenna array
of the radiation pattern of the designed antennas towards the angle with the lowest total path losses. Hence, to calculate the channel capacity in this design, we have considered the gain that was achieved by the MIMO antenna arrays at the incidence angle with the lowest loss. The total path loss versus the incidence angle of transmission for a multiple input/multiple output (MIMO) (2×2 system configuration) is shown in Fig. 14, where $S_{p1} = 1\text{m}$, $S_{p1} = 0.75\text{m}$, $L_{ij} = 2\text{m}$, $d_r = 0.1\text{m}$ and $d_r = 0.5\text{m}$. For the first transmit antenna and the first receive antenna, which is equivalent to the case of the second transmit antenna and the second receive antenna, the best incidence angle was observed at $47^\circ$ with a total path loss of 46.46 dB. For the first transmit antenna and the second receive antenna, the best incidence angle was observed at $45^\circ$ with a total path loss of 47.73 dB. Whereas, the second transmit antenna and the first receive antenna, the best incidence angle was observed also at $45^\circ$ with a total path loss of 46.72 dB. The channel capacity for the 2×2 MIMO system configuration with different transmit power is shown in Fig. 15, the capacity was 23.64 and 23.42 bit/s/Hz for MIMO antenna arrays 2 and 1 compared with 21.42 bit/s/Hz for MIMO antenna array 0. Based on the obtained results, the capacity performance was
enhanced when the photonic crystals were employed as seen in MIMO antenna arrays 2 and 1. Therefore, a 2×2 system based on MIMO antenna array 2 has achieved the maximum capacity. The capacity for different system configurations based on MIMO antenna array 2 comprising single input/single output (SISO) (1×1), multiple input/single output (MISO) (2×1), single input/multiple output (SIMO) (1×2) was investigated and compared to the 2×2 MIMO system configuration. The results are presented in Fig. 16. The capacities were 13.64, 14.59, and 14.85 bit/s/Hz for SISO, MISO and SIMO system configurations, respectively compared to 23.64 bit/s/Hz for the MIMO system configuration. Hence, an overall enhancement in the capacity performance was obtained with the MIMO system configuration compared to the MISO, SIMO, and SISO system configurations, respectively. The effect of the distance between the transmitter antennas $d_t$ and the receiver antennas $d_r$ on the total path loss and the channel capacity in the MIMO system configuration using MIMO antenna array 2 were investigated by sweeping $d_t$ from 0.1 to 0.3 m and $d_r$ from 0.2 to 1 m, respectively. Fig. 17 shows the total loss versus the incidence angle of transmission between each transmission antenna and receiver antenna. It is clear that the total path loss was increased by increasing the spacing between the transmitters and the receivers.
due to the added diversity scheme, moreover, a slight increase in the best incident angle of transmission was noticed. Fig. 18a shows the capacities for different transmitter spacing as 23.64, 24.85, and 24.69 bit/s/Hz at a transmission power of $10^3 \mu W$. Whereas, Fig. 18b shows the capacities for different receiver spacing as 22.5, 23.64, and 23.16 bit/s/Hz at a transmission power of $10^3 \mu W$. The results indicate that the capacity can be improved by varying the transmitter and the receiving spacing. The impact of the horizontal distance between the transmitter antennas and the receiver antennas using MIMO antenna array 2 for the MIMO system configuration was investigated further by sweeping $L_{ij}$ from 1 to 4 m. The total path loss versus the incidence angle of transmission is shown in Fig. 19. It is noticed that the total path loss was reduced when the horizontal distance was larger with a slight increase in the best incident angle of transmission. Fig. 20 shows the capacities at a transmission power of $10^3 \mu W$ which were found as 17.13, 23.64, and 17.08 bit/s/Hz, so, the capacity decreased by increasing the horizontal distance.
For the scenario presented in Fig. 13, the maximum capacity was 23.64 bit/s/Hz at a transmission power of $10^3 \, \mu W$ for the $2 \times 2$ system configuration using the MIMO antenna array based on the optimized photonic crystals. For the same scenario, this capacity clearly is favorable compared to 11.5 bit/s/Hz by (Xu et al. 2014), 18.21 bit/s/Hz by (Temmar et al. 2021) and 22.3 bit/s/Hz by (Esfandiyari et al. 2019). This capacity can be improved further by using larger system scales or by manipulating the spacings and distances between the transmit and the receive antennas.

5 Conclusion

In this paper, a novel MIMO system was developed using a graphene-based $1 \times 2$ microstrip patch antenna array using different substrates, including homogeneous, periodic photonic crystals and optimized photonic crystals substrates. Based on the properties of graphene, the graphene load operated in a low resistive mode where the chemical potential $\mu_c$ is used as 1.5 ev. The obtained results have shown noticeable enhancements around 0.65 THz in the gain and the bandwidth with the values of 11.80 dB and more than 614 GHz, respectively when a MIMO antenna array employing based on the optimized photonic crystals was considered. Next, an indoor communication environment based on the terahertz band was studied and analyzed in which the total path loss and channel capacity were numerically calculated. The results showed that the proposed $2 \times 2$ MIMO system with a MIMO antenna array based on the optimized photonic crystals substrate achieved the highest capacity of 23.64 bit/s/Hz in the highest transmit power compared to 23.42 bit/s/Hz and 21.42 bit/s/Hz obtained by the same $2 \times 2$ MIMO system using MIMO antenna array based on the periodic photonic crystals and the homogeneous substrates, respectively. Finally, an interesting improvement in the channel capacity was achieved by manipulating the geometrical parameters of the indoor environment.

Acknowledgements This study was supported by the Algerian Ministry of Higher Education and Scientific Research through funding for PRFU Project
Author Contributions We are enclosing herewith a manuscript entitled “Design and analysis of MIMO system for THz communication using terahertz patch antenna array based on photonic crystals with graphene” for publication in Optical and Quantum Electronics Journal. With the submission of this manuscript I would like to undertake that: All authors of this research paper have directly participated in the planning, execution, or analysis of this study; All authors of this paper have read and approved the final version submitted; The contents of this manuscript have not been copyrighted or published previously; The contents of this manuscript are not now under consideration for publication elsewhere; The contents of this manuscript will not be copyrighted, submitted, or published elsewhere, while acceptance by the Journal is under consideration; There are no directly related manuscripts or abstracts, published or unpublished, by any authors of this paper.

Funding The authors have not disclosed any funding

Availability of data and materials The availability of data and materials are owned by the authors.

Declarations

Conflict of interest The authors have not disclosed any conflict of interest.

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