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REVIEW

# Low complexity but near optimal hybrid beamforming design in tera-hertz communication systems: principles and opportunities

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**Abstract**

Next generation communication systems go to tetra-hertz (THz) frequency bands. In this article, low-complexity but near-optimal hybrid beamforming design is investigated in THz by considering its unique channel characteristics and discuss potential research opportunities. Specifically, the THz channel characteristics are explored from its propagation feature, angular orthogonality and bandwidth. The authors clarify the differences between the THz multiple-input-multiple-output (MIMO) and its low-frequency counterparts (e.g. mmWave MIMO). Low complexity but near-optimal hybrid beamforming design in THz are summarised in the following typical scenarios, namely the single-user and multi-user downlink system, integrated data and energy transfer system and the intelligent reflecting surface aided system. Simulation results demonstrate the near-optimality of our hybrid beamforming design. Some critical open issues in the THz communication system are discussed for future research interest.

**KEYWORDS**

5G mobile communication, beam steering, MIMO communication, optimisation, terahertz waves

## 1 | INTRODUCTION

6G supports new applications, such as extremely-high-definition video transmission, virtual reality, holographic communication and pervasive Internet of Everything (IoE) while the peak data rate is expected to be higher than 1 Tbps [1, 2]. In order to accommodate extremely-high tele-traffic, mobile communication systems in 6G go to tera-hertz (THz) bands, which are around 0.1–10 THz.

In order to overcome severe path-loss in THz bands, multiple antennas are adopted. Thanks to the extremely short wavelength, ultra-massive antennas can be compactly implemented at both transmitters and receivers, which results in abundant spatial gains. However, full-digital transceivers are unaffordable due to high hardware cost and energy consumption. Therefore, a hybrid architecture is adopted by considering both digital and analogue beamforming design. Amirifar et al. [3] design the power allocation to maximise the sum rate problem in massive multiple-input-multiple-output (MIMO) non-orthogonal multiple access system. Although it has been widely studied in the millimetre-wave (mmWave) band, new challenges and opportunities emerge due to the unique propagation characteristics of the THz channel [4].

Initial exploration has commenced on the hybrid beamforming in THz. Yuan et al. [5] designed a hybrid beamfomer for MIMO THz systems over frequency selective fading channels. Lin et al. [6] investigated a codebook-based hybrid beamfomer for maximising the sum-rate of a multi-user THz system. However, they designed the analogue beamformer by adopted codebook-based algorithms, which is the same as that in mmWav, while it yielded a high-complexity solution with a compromised performance. The unique characteristics of THz was ignored.

THz communications rely upon the line of sight (LoS) path. Therefore, an intelligent reflecting surface (IRS) is a good choice to create the virtual LoS path from the transmitter to the user [7]. Furthermore, an IRS is equipped with a large reflector array, which is suitable for forming high directional reflecting beams towards the users in the THz band [8]. Liu et al. [9] studied a THz IRS-aided integrated sensing and communication system. They designed the transmit beamformer and reflecting beamformer to maximise the long-term spectral efficiency. Pan et al. [10] investigated an IRS-assisted THz communication system. They maximised the sum rate of all users by optimising the hybrid beamformer, bands allocation and reflecting beamformer. In the future pervasive IoE, quickly drained batteries largely limit the performance of miniature devices [11]. Therefore, radio frequency (RF) signals are relied upon for integrated data and energy transfer (IDET) [12]. Pan et al. [13] considered an IRS-aided THz IDET system. They designed the hybrid beamformer and reflecting beamformer to maximise the achievable rate while guaranteeing the energy requirements. However, their passive beamforming design still adopted alternative optimisation-based algorithms, which yielded a high computational complexity since the THz channel characteristics were not considered.

Against this background, our novel contributions are summarised as follow:

(1) We explore the signal propagation feature, bandwidth and angular orthogonality in THz channels. We clarify the differences between the THz channel and its low-frequency counterparts (e.g. mmWave channel) in terms of coherent bandwidth and orthogonality, which guides us to obtain closed form and near-optimal hybrid beamforming design with low complexity in implementation.
(2) A single-user THz communication system is studied. An analogue beamformer with a single RF chain achieves near-optimal performance compared to the optimal full-digital counterpart. The hardware complexity is substantially reduced, while the analogue beamformer achieves almost 99.9% performance as the optimal full-digital counterpart from the simulation results.
(3) The hybrid beamformer is designed in a multi-user THZ system. The closed-form asymptotically optimal analogue beamformer is found, while asymptotically optimal structure of the corresponding digital beamformer is obtained, which largely reduces both the computation and hardware complexity. The performance of the proposed hybrid beamformer is closed to the optimal full-digital counterpart. The hybrid beamformer design is extended to an IDET system in THz. The balance between the wireless data transfer (WDT) and the wireless energy transfer (WET) can be flexibly adjusted by the power allocation in the digital domain.
(4) An IRS-aided THz communication system is studied, where the LoS paths from the transmitter to the users are blocked. A novel asymptotically optimal passive beamformer is founded in closed form for the IRS. We reveal that the IRS cannot introduce any additional multiplexing gain due to the spatial sparsity of THz channels. By contrast, the multiplexing gain can only be increased by implementing multiple IRSs.

## 2 | CHANNEL CHARACTERISTICS IN THZ

### 2.1 | Channel sparsity

As shown in Figure 1, the channel in low frequency has rich scatters, while mmWave contains several scattering clusters, each of which contributes some propagation paths. A THz channel consists of a LoS path and a few non-LoS (NLoS) paths. In every path, the channel coefficient is determined by the large-scale path-loss, the small-scale fading and the angle of

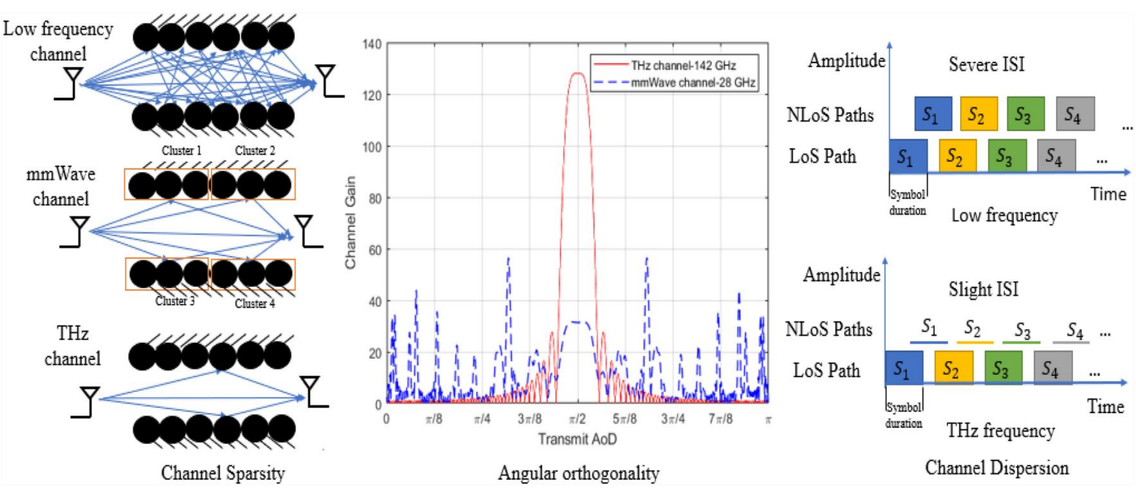


**FIGURE 1** Tera-hertz (THz) channel characteristics.

departure (AoD). Note that the NLoS paths always have substantially higher path-loss than the LoS path due to serious absorption of the propagation environment and the lack of the diffraction in THz [14]. As a result, channels in THz are spatially sparse, when comparing to the low-frequency cases. We only need to focus on the LoS path to design the transmit beamformer.

### 2.2 | Angular orthogonality

Angular orthogonality may be arranged between any pair of users in the THz bands. When we have an infinite number of transmit antennas, any two channel response vectors generated with different AoDs are orthogonal with each other. As a result, we only need to adjust the phase of the transmit beam in the analogue domain to achieve the orthogonality.

The angular orthogonality is characterised in Figure 1. The gain of the NLOS path is 20 dB less than that of the LOS path in many reference [5, 15], which is also confirmed in THz channel measurement according to the authors in Ref. [16]. The number of NLoS paths is set to three. The number of transmit antennas is set to 128. The AoD of the channel response vector towards one user is set to $\pi/2$ while we generate another channel response vector towards a different user with an AoD ranging from zero to $\pi$. Observe from Figure 1 that the inner product of these two channel response vectors is maximum, when they have the same AoD. Moreover, the inner-product only has a single peak in THz, when we change the transmit AoD since the spatial gain mainly comes from the LoS path, which also confirms the spatial sparsity. When the transmit AoD tracks the LoS path, the maximum spatial gain is obtained. The reason is that the LoS path is far stronger than the NLoS counterpart. Furthermore, their inner-product reduces to zero as the difference between these two AoDs becoming larger, which confirms the angular orthogonality. Note further that some special AoDs have zero inner-product, which can be relied upon for generating an orthogonal codebook in THz. By contrast, observe from Figure 1 that multiple inner-product peaks exist in the mmWave band. The reason is that the NLoS paths cannot be ignored. When the transmit AoD is equal to one of these NLoS path in the mmWave channel, additional spatial gain can be obtained. However, the optimal performance cannot be guaranteed with strict hardware limitation.

### 2.3 | Channel dispersion

Low-frequency results in a number of scattering NLoS paths. The resultant multipath transmission constitutes small-scale fading, which is normally modelled as either a Rayleigh distribution or a Rician distribution. When the signal transmission bandwidth is wider than the coherent bandwidth, it results in the frequency selective fading. Furthermore, a wider bandwidth also corresponds to a small symbol duration, which may result in severe intern-symbol-interference (ISI), which is known as channel dispersion effect. As shown in Figure 1, the symbol $S_1$ transmitted in the NLoS paths imposes strong interference on the subsequent symbol $S_2$ in the low-frequency band. The reason is that the signal strength after propagating in the NLoS paths is still strong. In order to avoid the ISI incurred by wider bandwidth, the classic multi-carrier communication system is proposed to reduce the signal bandwidth without sacrificing the wideband gain, such as the orthogonal-frequency-multiple-multiplexing (OFDM).

By contrast, in the THz band, due to their ultra-short wavelength, signals are substantially absorbed by miniature obstacles. Therefore, the ISI incurred by the channel dispersion effect can be reasonably ignored [17]. As shown in Figure 1, the symbol $S_1$ transmitted from the NLoS paths only imposes weaker interference on the subsequent symbol $S_2$. By exploiting this feature, Sen et al. [18] implements a practical single-carrier THz hardware platform with a bandwidth of 1.76 GHz.

The THz channel is analysed from three aspects namely channel sparsity, angular orthogonality and channel dispersion. Based on our analysis, two hybrid beamformer design principles are concluded, which is summarised as follows:

1. Principle 1: Full-channel gain is almost achieved in the analogue domain, while the analogue beamformer only tracks the LoS path in THz channel.
2. Principle 2: The asymptotical orthogonality is achieved in the analogue domain, which results in small interference of every user.

## 3 | LOW COMPLEXITY AND NEAR OPTIMAL HYBRID BEAMFORMER

The principles of the hybrid beamforming design in the following typical THz scenarios are investigated.

### 3.1 | Single-user THz communication system

The Maximum ratio transmit (MRT) beamformer is deemed to be optimal in a single user multiple-input-single-output (MISO) system. However, a MRT beamformer requires a full-digital architecture to adjust the phases and amplitudes at the transmitter. Unfortunately, it cannot be attained at a transmitter having a hybrid architecture in both mmWave and THz.

#### 3.1.1 | Transmitter architecture

The transmitter in THz is allowed to be equipped with a large number of antennas, since the wavelength is extremely short. It is unaffordable that each antenna is connected to a RF chain, which may result in very high hardware and energy cost. As a result, a hybrid structure is widely investigated, as shown in Figure 2, where multiple transmit antennas share a common RF chain. The baseband digital beamformer forwards the

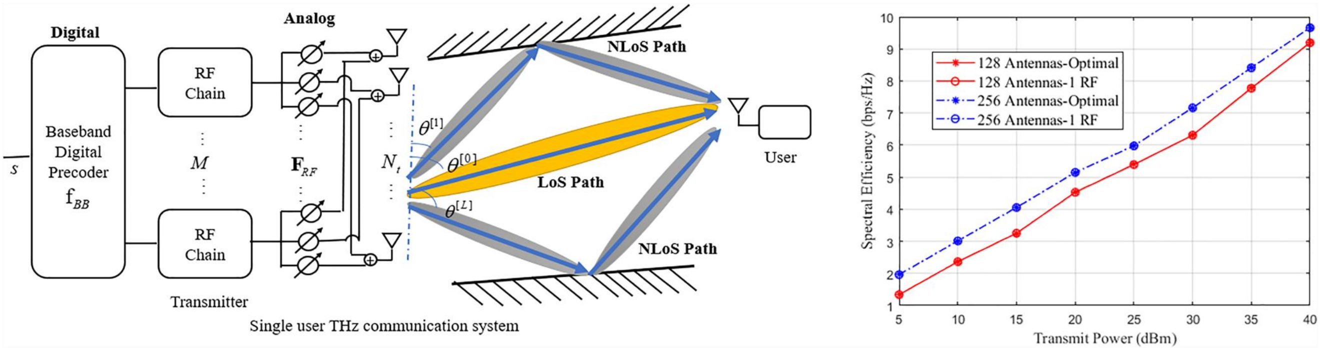


**FIGURE 2** Spectral efficiency in single user communication system.

modulated symbols to the RF chains. Then, the passband analogue beamformer further adjusts the phase of the output RF signals before they can be transmitted by the antennas. Note that the performance of a hybrid beamformer is poorer than its full-digital counterpart since the limited number of RF chains reduces the degree of freedom in the spatial domain. However, by exploiting the characteristics of the THz channels, the hybrid beamformer may achieve almost the same communication performance as the full-digital solution.

### 3.1.2 | Analogue beamforming design in THz

In mmWave, signal propagation exhibits clustering effects. The channel is assumed to be the sum of the contributions from some scattering clusters, each of which has several strong propagation paths, as exemplified in Figure 1. Therefore, the NLoS paths cannot be ignored. To achieve the optimal beamformer, we have to exploit all the spatial gains of all the LoS and NLoS paths. As a result, the number of the RF chains at the transmitter should be equal to the number of transmission paths in a mmWave channel while all the RF chains also have to be fully connected to all the transmit antennas. Every RF chain adjusts the phase to track a specific transmission path while it adjusts the amplitude to match the fading gain in that path. However, a typical mmWave channel may have more than 80 different transmission paths [19]. It means that the transmitter needs the same number of RF chains to obtain the optimal performance. Unfortunately, this is practically unaffordable. Therefore, we can only obtain a compromised performance in a hybrid architecture, given a limited number of RF chains is lower than the number of transmission paths.

However, we can achieve almost the same performance by relying on a single RF chain as the optimal MRT beamformer in THz. When we consider the single user communication system, we only need a RF chain to achieve almost the same performance as the optimal full-digital beamformer according to Principle 1. The analogue beamformer is equal to the phases of the channel response vector with the same AoD as the LoS path, which achieves almost full spatial-gain as the full-digital counterpart. The reason is that the THz channel only have a single strong LoS path, while the other week NLoS paths contribute little to the spatial gain. Therefore, the transmitter only needs a single RF chain to track the dynamic change of the LoS path. We can obtain the near-optimal performance by only relying on the analogue beamformer with a single RF chain, which has extremely low hardware and computation complexity.

### 3.1.3 | Performance analysis

In Figure 2, the spectral efficiency of a single-user THz system is characterised. The number of NLOS paths is set to three [6]. The path-loss of the NLoS path is 20 dB higher than that of the LoS path [6]. The noise power is set to −75 dBm, while the transmit power is set to 30 dBm. The path-loss of LoS path is 90 dB when the carrier frequency is 142 GHz and the distance from the transmitter to all the users is 5 m. The optimal beamformer is the full-digital MRT one, while legend '1-RF' represents our proposed analogue beamformer enabled by a single RF chain. The hardware complexity of our analogue beamfomer is far lower than that of the full-digital counterpart. Observe from Figure 2 that our proposed analogue beamformer performs similarly to its optimal counterpart. We only need to focus the beam on the strong LoS path to achieve the near-optimal performance.

### 3.1.4 | More discussions

Apart from a full-connection structure of a hybrid beamforming-aided transmitter, we may also study partial-connection structures in which a RF chain is only connected to a few number of antennas. This structure consumes less energy than the full-connection one. How to design the corresponding optimal hybrid beamformer for them is still an open problem.

## 3.2 | Multi-user THz communication/IDET system

As shown in both Figures 3 and 4, we have a transmitter with a large antenna array and several users with a single antenna. The

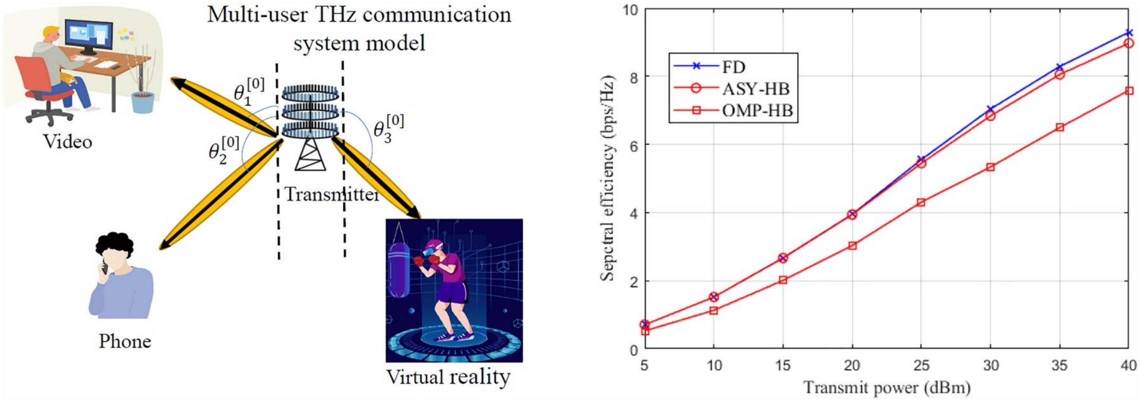


**FIGURE 3** The spectral efficiency in the multi-user tera-hertz (THz) communication system.

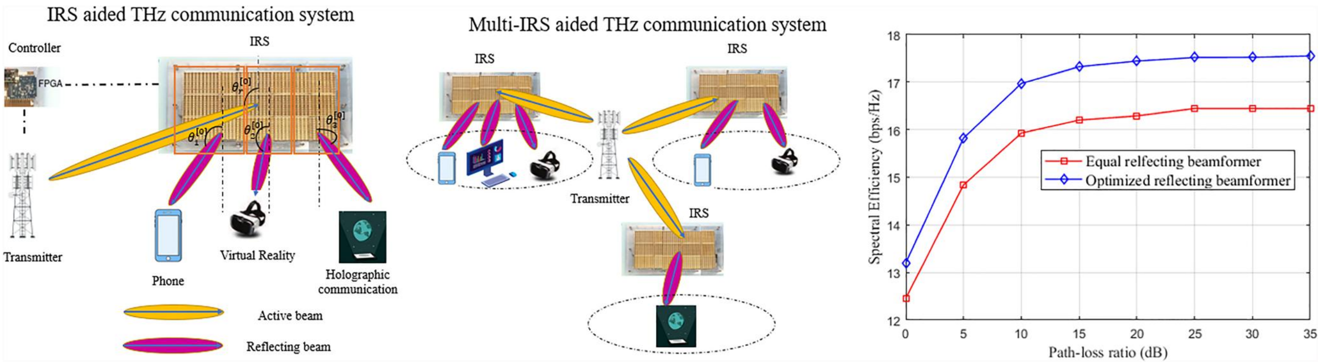


**FIGURE 4** Trade-off between spectral efficiency and energy in integrated data and energy transfer system.

transmitter delivers either communication or IDET services towards these users.

### 3.2.1 | Hybrid beamformer design for communications

The asymptotically optimal analogue beamformer is determined by the AoD of the LoS paths towards all the downlink users, when the number of transmit antennas tend to infinity. Based on the angular orthogonality, we do not need full channel state information (CSI) for designing the analogue beamformer. When the multi-user down-link communication system are considered, the asymptotically optimal analogue beamformer aiming for a specific user is simply the conjugate of the channel response vector of the LoS path, whose phases are solely determined by the corresponding AoD according to Principle 1.

Every RF chain only allocates transmit power towards a specific user, which can be designed in the digital domain. Therefore, the required number of RF chains is equal to that of the users, which is far lower than that of the full-digital counterpart. When the transmitter multicasts a common message to all the users, there is no mutual interference for all the user. Suppose that the number of RF chains is equal to the number of the users. Therefore, the digital beamformer is a vector. Based on the asymptotically optimal analogue beamformer, the $i$th element in the corresponding asymptotically optimal digital beamformer represents the allocated power towards the $i$th user. When the transmitter broadcasts different messages to these users, given the asymptotically optimal analogue beamformer, the interference is very small since any two beam are asymptotically orthogonal to each other according to Principle 2. Therefore, the corresponding asymptotically optimal digital beamformer should be a diagonal matrix. The $i$th diagonal element is the power allocated to the $i$th user. The reason is that we need to improve the strength of the desired signal, while suppressing the mutual interference.

### 3.2.2 | Performance analysis

The impact of our hybrid beamforming design on the spectral efficiency is characterised in a multi-user THz system in Figure 3. The system has three users. The transmitter is equipped with 128 transmit antenna and three RF chains. The number of NLOS paths is set to three [6]. The path-loss of the NLoS path is 20 dB higher than that of the LoS path [6]. The noise power is set to −75 dBm, while the transmit power is set to 30 dBm. The path-loss of LoS path is 90 dB when the carrier frequency is 142 GHz and the distance from the transmitter to all the users is 5 m. The optimal full-digital beamformer is denoted as ‘FD’, while our proposed hybrid beamformer and the orthogonal matching pursuit (OMP)-based hybrid beamformer [19] are denoted as ‘ASY-HB’ and ‘OMP-HB’, respectively. Note that our proposed hybrid beamfomer only requires three RF chains. The analogue beamformer is obtained in a closed form. Both computation and hardware complexity of our hybrid beamformer are far lower than the full-digital counterpart. Observe from Figure 3 that the performance of our proposed hybrid beamformer is close to that of the full-digital counterpart, while it is much higher than the OMP-based counterpart. The reason is that our hybrid beamformer tracks the LoS path of every user, which achieves almost full spatial-gain and reduce the mutual interference.

#### 3.2.3 | Hybrid beamforming design for IDET

As shown in Figure 4, the transmitter simultaneously provides WDT services to $K$ information users (IUs) and WET services to $L$ energy users (EUs) with $(K + L)$ RF chains. For each user, we need a RF chain to track the corresponding LoS path. In the IDET system, the analogue beamformer adjusts the phase of the beams towards all the IUs and EUs, while the digital beamformer allocates the transmit power to the corresponding IUs and EUs from Principle 2. There is a trade-off between the WDT performance of the IUs and the WET performance of the EUs, which depends on the power allocation in the digital beamformer.

#### 3.2.4 | Performance analysis

The trade-off between the spectral efficiency and energy harvesting requirements is investigated in the THz IDET system in Figure 4. The system has three information users and two energy users. The transmitter is equipped with 128 transmit antennas and four RF chains. The number of NLOS paths is set to three [6]. The path-loss of the NLoS path is 20 dB higher than that of the LoS path [6]. The noise power is set to −75 dBm, while the transmit power is set to 30 dBm. The receive antenna gain of the energy user is set to 25 dBi. The path-loss of the LoS path are 90 and 60 dB, when the carrier frequency is 142 GHz and the distances from the transmitter to all the information users and from that to all energy user are 5 and 1 m. The equal beamformer is the transmitter allocates the same power to all the users in the digital beamformer, while its analogue beamformer is the same as our optimal design. Observe from Figure 4 that the spectral efficiency of IUs degrades as we increase EUs' energy harvesting requirements. The energy ratio is defined as the percentage of the transmit power allocated for WET. As the energy harvesting requirement increase, more power is allocated to WET in the digital domain, which results in a higher energy ratio. Note that our hybrid beamforming design achieves a much larger rate-energy region than the equal beamformer.

#### 3.2.5 | More discussions

Our multi-user hybrid beamformer design can be adopted in many problems, for example, maximising the sum rate or the secrecy rate. When we consider the limited resolution of the phase shifters, the angular orthogonality is not as remarkable as the continuous counterpart. How to design the hybrid beamformer with this hardware impairment is essential.

### 3.3 | IRS aided THz communication

As shown in Figure 5, an IRS-aided THz communication system has a single transmitter with a large antenna array, an IRS with a large reflector array and multiple users with a single antenna. We consider that the LoS path from the transmitter to all the users are blocked. By implementing an IRS, we may create virtual LoS paths for restoring THz communications.

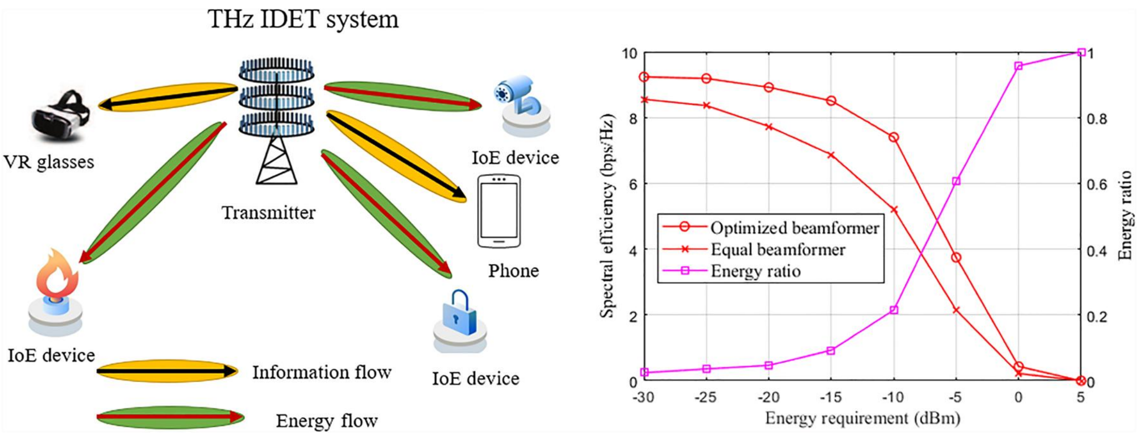


**FIGURE 5** Spectral efficiency versus the ratio between the line of sight (LoS) channel and non-LoS channel in the intelligent reflecting surface (IRS) aided tera-hertz (THz) system.

### 3.3.1 | Passive beamformer design with a single IRS

In the IRS-aided THz communication system, we mainly focus on the passive beamformer design at the IRS in the analogue domain, while the hybrid beamformer design at the transmitter is similar to the previous discussion. Note that both principles are also available for the passive beamformer. When we consider a single user in the system, the optimal passive beamformer of the IRS adjusts the reflecting beam towards the user according to Principle 1. In order to simultaneously support multiple users, the IRS is virtually divided into several parts, each of which adjusts the phases of the incident signals in order to let the reflecting signals aiming at the target user. Each part achieves almost near-optimal performance from Principle 1 while any two reflecting beams by different part of IRS are asymptotically orthogonal according to Principle 2. The AoD of the passive beamformer in every part is to adjust the angle of arrival (AoA) of the LoS path from the transmitter to the IRS so that the reflecting angle is the same as the AoD of the LoS path from the IRS to the target user. The number of reflectors $M$ in each part depends on the QoS requirements of the target user, while the achievable rate grows in the $\log(M^4)$ level with respect to the number of reflectors. Therefore, we may obtain the closed-form passive beamformer.

As a result, the proposed asymptotically optimal passive beamformer of the IRS is able to track the LoS paths of all the users, which achieves the full spatial-gain.

### 3.3.2 | Passive beamformer design with multiple IRSs

However, a single IRS cannot introduce additional multiplexing gain. The reason is that multiple date flows from the transmitter has to target this IRS. Therefore, after they are multiplexed by the transmitter, both the desired signal and the interference towards a single user are strengthen by the IRS since the passive IRS does not have any RF chains for signal processing. Therefore, the signal-to-interference ratio (SIR) is not improved.

In order to increase the degree of freedom, the multiple IRSs have to be implemented since they may create more LoS paths and thus increase the spatial gains for multiplexing.

The hybrid beamformer in the transmitter is similar to that in Section 3.2. The analogue beamfomer aims for all the IRSs, while the digital beamformer determines the power allocated to every IRS. The passive beamformer in every IRS is the same as the single IRS design.

### 3.3.3 | Performance analysis

The impact of the path-loss ratio between the LoS path and the NLoS path on the spectral efficiency in a single IRS-aided THz communication system is investigated. The system has three users. The transmitter is equipped with 128 transmit antennas and three RF chains. The number of NLOS paths is set to three [6]. The path-loss of the NLoS path is 20 dB higher than that of the LoS path [6]. The noise power is set to −75 dBm, while the transmit power is set to 30 dBm. The path-loss of the LoS path is 90 dB, when the carrier frequency is 142 GHz and the distance from the transmitter to all the users is 5 m. Moreover, path-loss is 95 dB when the distance of the transmitter-IRS-user link is 6 m at the same centre frequency. The number of the reflector in the IRS is set to 1000. The equal passive beamformer is to group the same number of reflectors for every user while it has the same hybrid beamformer at the transmitter as its counterpart. As shown in Figure 5, the spectral efficiency increases when the path-loss ratio is from 0 to 15 dB. The reason is that we only choose the LoS path to transfer information from the transmitter to the IRS and that from the IRS to the users. When the path-loss ratio is set to 0 dB, the NLoS paths are as strong as the LoS path. Therefore, our design cannot achieve the full spatial-gain since it ignores all the NLoS paths. With a higher path-loss factor, the LoS channel becomes more prominent, which results in an increasing spectral efficiency. Moreover, our passive beamformer design achieves a higher spectral efficiency than the equal counterpart.

### 3.3.4 | More discussions

Our passive beamformer design can be applied in many scenarios. For example, the IRS consumes energy when we adjust the phase of the IRS. How to design the passive beamformer to minimise the energy consumption in a long period is still an open problem. Furthermore, the channel estimation is difficult to obtain in the IRS cascaded channel. Our passive beamformer design can largely reduce the complexity in the robust design with imperfect channel state information.

# 4 | OPEN RESEARCH ISSUES

## 4.1 | Ultra-wide bandwidth and coloured noise

The bandwidth of a THz communication system is normally ranging from 0.56 THz to 0.74 THz. This ultra-wide bandwidth results in the frequency selective and non-stationary Gaussian noise. Multicarrier is still a fancy technology to overcome the channel dispersion and its resultant ISI. Efficiently exploiting the wide bandwidth is still an open problem in the THz band. We may explore the hybrid beamformer design in frequency selective noise and the wide bandwidth channel.

## 4.2 | Near-field THz communication

The propagation characteristics of near-field THz is different from that of far-field THz [20]. For example, the fading coefficient is related to the antenna position. Furthermore, the antenna position also influences the performance of hybrid beamformer. Therefore, the joint hybrid beamformer and antenna position design are indispensable for near-field THz communication.

### 4.3 | Holographic MIMO THz communication

The transmitter is usually equipped with a large antenna-array in THz. However, it results in the mutual coupling among closely spaced antennas. In the holographic MIMO-THz system, we may use metamaterial antennas to solve this problem [21]. The size of the metamaterial antenna and the space between nearby the metamaterial antennas are much smaller than half of the wavelength, which can be regarded as a continuous aperture, especially when the number of the transmit antennas tend to infinity. Therefore, we use the effective baseband channel model in holographic MIMO. Designing the holographic beamformer by considering the continuous aperture effect is essential to further improve the communication performance.

## 5 | CONCLUSION

The basic principle of hybrid beamforming design in THz is introduced by considering its unique channel features. First, angular orthogonality is obtained by exploiting the spatially sparse nature of the THz channel. Then, typical THz systems are studied, which includes a single-user/multi-user THz communication system, a THz IDET system and an IRS aided THz system. Some exemplary simulation results demonstrate the advantage of our hybrid beamforming design in THz. At last, open challenges are provided for stimulating future research interest.

## AUTHOR CONTRIBUTIONS

**Qingdong Yue:** Formal analysis; Investigation; Software; Writing – original draft. **Jie Hu:** Conceptualisation; Methodology; Project administration; Supervision; Validation; Writing – review and editing. **Kun Yang:** Funding acquisition; Resources; Validation; Writing – review and editing.

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## CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

## DATA AVAILABILITY STATEMENT

There is no data available. The data are available from the corresponding author on reasonable request.

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## REFERENCES

1. Chen, Z., et al.: Terahertz wireless communications for 2030 and beyond: a cutting-edge frontier. IEEE Commun. Mag. 59(11), 66–72 (2021). https://doi.org/10.1109/mcom.011.2100195
2. Guan, K., et al.: Scenario modules, ray-tracing simulations and analysis of millimetre wave and terahertz channels for smart rail mobility. IET Microw., Antennas Propag. 12(4), 501–508 (2018). https://doi.org/10.1049/iet-map.2017.0591
3. Amirifar, Z., Abouei, J.: The dynamic power allocation to maximize the achievable sum rate for massive mimo-noma systems. IET Commun. 16(17), 2036–2044 (2022). https://doi.org/10.1049/cmu2.12457
4. Sheikh, F., Zarifeh, N., Kaiser, T.: Terahertz band: channel modelling for short-range wireless communications in the spectral windows. IET Microw., Antennas Propag. 10(13), 1435–1444 (2016). https://doi.org/10.1049/iet-map.2016.0022
5. Yuan, H., et al.: Hybrid beamforming for Terahertz multi-carrier systems over frequency selective fading. IEEE Trans. Commun. 68(10), 6186–6199 (2020). https://doi.org/10.1109/tcomm.2020.3008699
6. Lin, C., Li, G.: Adaptive beamforming with resource allocation for distance-aware multi-user indoor Terahertz communications. IEEE Trans. Commun. 63(8), 2985–2995 (2015). https://doi.org/10.1109/tcomm.2015.2440356
7. Wu, Q., Zhang, R.: Towards smart and reconfigurable environment: intelligent reflecting surface aided wireless network. IEEE Commun. Mag. 58(1), 106–112 (2020). https://doi.org/10.1109/mcom.001.1900107
8. Basharat, S., et al.: Exploring reconfigurable intelligent surfaces for 6g: state-of-the-art and the road ahead. IET Commun. 16(13), 1458–1474 (2022). https://doi.org/10.1049/cmu2.12364
9. Liu, X., et al.: Proximal policy optimization-based transmit beamforming and phase-shift design in an irs-aided isac system for the thz band. IEEE J. Sel. Areas Commun. 40(7), 2056–2069 (2022). https://doi.org/10.1109/jsac.2022.3158696
10. Pan, Y., et al.: Sum-rate maximization for intelligent reflecting surface assisted terahertz communications. IEEE Trans. Veh. Tech. 71(3), 3320–3325 (2022). https://doi.org/10.1109/tvt.2022.3140869
11. Jie, H., et al.: Integrated data and energy communication network: a comprehensive survey. IEEE Commun. Surv. Tutor. 20(4), 3169–3219 (2018). https://doi.org/10.1109/comst.2018.2860778
12. Hu, J., Wang, Q., Yang, K.: Energy self-sustainability in full-spectrum 6g. IEEE Wireless Commun. 28(1), 104–111 (2021). https://doi.org/10.1109/mwc.001.2000156
13. Pan, Y., et al.: Self-sustainable reconfigurable intelligent surface aided simultaneous terahertz information and power transfer (stipt). IEEE Trans. Wireless Commun. 21(7), 5420–5434 (2022). https://doi.org/10.1109/twc.2022.3140268
14. Do, H., et al.: Terahertz line-of-sight mimo communication: theory and practical challenges. IEEE Commun. Mag. 59(3), 104–109 (2021). https://doi.org/10.1109/mcom.001.2000714
15. Han, C., Jornet, J.M., Akyildiz, I.: Ultra-massive mimo channel modeling for graphene-enabled terahertz band communications. In: 2018 IEEE 87th Vehicular Technology Conference (VTC Spring), pp. 1–5 (2018)
16. Ju, S., et al.: Millimeter wave and sub-Terahertz spatial statistical channel model for an indoor office building. IEEE J. Sel. Areas Comm. 39(6), 1561–1575 (2021). https://doi.org/10.1109/jsac.2021.3071844
17. Han, C., Bicen, A.O., Akyildiz, I.F.: Multi-ray channel modeling and wideband characterization for wireless communications in the terahertz

band. IEEE Trans. Wireless Comm. 14(5), 2402–2412 (2015). https://doi.org/10.1109/twc.2014.2386335

18. Sen, P., et al.: A versatile experimental testbed for ultrabroadband communication networks above 100 ghz. Comput. Network. 193, 108092 (2021). https://doi.org/10.1016/j.comnet.2021.108092
19. Ayach, O.E., et al.: Spatially sparse precoding in millimeter wave mimo systems. IEEE Trans. Wireless Commun. 13(3), 1499–1513 (2014). https://doi.org/10.1109/twc.2014.011714.130846
20. Llombart, N., Dabironezare, S.O.: Feasibility study of quasi-optical mimo antennas for radiative near-field links. IEEE Trans. Antenn. Propag. 70(8), 7073–7083 (2022). https://doi.org/10.1109/tap.2022.3168724
21. Pizzo, A., Sanguinetti, L., Marzetta, T.L.: Fourier plane-wave series expansion for holographic mimo communications. IEEE Trans. Wireless Commun. 21(9), 6890–6905 (2022). https://doi.org/10.1109/twc.2022.3152965

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