Joint Radar and Communication Empowered by Digital Programmable Metasurface

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Digital programmable metasurfaces (DPMs) can dynamically modulate electromagnetic waves in space, time, and frequency domains with powerful capabilities. In contrast, joint radar and communication (JRC) is an important avenue to use the electromagnetic waves universally and intelligently. Hence, combining DPM and JRC may produce a promising way to achieve universal and intelligent electromagnetic terminals. Herein, a mechanism of extremely flexible JRC based on DPM is proposed, in which DPM can improve the flexibility of JRC in processing multidimensional information, and JRC endows DPM with the capabilities of perception, expression, and cognition to promote its intelligent level. Three kinds of functions are explored to interpret the mechanism. First, encryption and decryption of wireless secure communications are realized through DPM; second, range profile imaging is accomplished by using DPM-based biphase-coded signals; and third, wireless communication and radar detection are simultaneously presented using DPM. The combination of DPM and JRC greatly decreases the complexity of signal processing and simplifies the architecture of the JRC system, and promotes the intelligent level of DPM.

1. Introduction

Metasurfaces can manipulate electromagnetic waves artificially,[1–8] but this characteristic can hardly be considered as artificial intelligence, because an intelligent entity should possess the abilities to implement internal decisions and exchange information with the external world. A feasible way to acquire these abilities is to combine the metasurface with electronic information systems. Digital programmable metasurface (DPM) is a kind of metasurface whose unit element is digitally reconfigurable.[9–18] Configured by adequate aperture codes, DPMs can dynamically control amplitude, phase, polarization, and vortex states of the electromagnetic waves. Massive researches about DPMs have emerged, such as computational imaging[19–23] and metasurface-based signal modulation and transmission.[24–34] Technically, DPMs are directly driven by digital signals and possess the characteristics of software and informatization, and hence are perfect platforms for combining the metasurfaces with electronic information systems. However, the intelligent level of DPMs is still limited, because the presented DPMs cannot simultaneously conduct internal decisions and exchange information with the external world.

As the most important kinds of electronic information systems, wireless communication and radar systems have been developed independently for many years. Generally, the radar systems aim to estimate the channel information with known source signals, whereas the communication systems aim to estimate the source signals with known channel information. Driven by new civil and military requirements such as 6G wireless communication, smart city, and intelligent cooperative operation, the radar detection and wireless communication show a trend of convergence. Joint radar and communication (JRC)[35–37] was proposed to realize radar and communication functions simultaneously by using the same platform and the same signal. Actually, JRC has returned to the essence that the electromagnetic waves function as the information carriers, and it is in this essential sense that JRC becomes an important avenue to realize integrated, universal, and intelligent electromagnetic platforms. Currently, the JRC systems process signals mainly in the time and frequency domains, and only the JRC systems equipped with phased array antennas or multiple-input-multiple-output (MIMO) antennas can deal with the signals involving spatial information, but they consequently lead to difficult signal processing and complicated system architectures.

Combining DPM and JRC will produce a promising orientation to realize the universal and intelligent electromagnetic systems. DPM can improve the flexibility of JRC in processing multidimensional information, and JRC endows DPM with the capabilities of perception, expression, and cognition. More specifically, the spatial processing of signals in JRC can be decoupled in DPM, thus greatly decreasing the complexity of signal processing and simplifying the architecture of the system.
Meanwhile, the signal processing capacity of JRC greatly promotes the intelligent level of DPM. With this combination, JRC can serve as a brain of DPM, and DPM has actually evolved to an intelligent electromagnetic terminal.

A schematic diagram of the DPM-based JRC is shown in Figure 1. The information carried by the electromagnetic waves is transmitted and received through DPM, and is evaluated and processed by the JRC kernel software. This procedure is very similar to human behaviors such as talking, watching, hearing, and thinking. In this work, we present several experiments to illustrate the DPM-based JRC: 1) encryption and decryption of wireless secure communication on the DPM aperture; 2) range profile imaging of multiple targets by using DPM-based biphase-coded signals; and 3) realizing radar detection and wireless communication independently and simultaneously through DPM. These works show that the DPM-based JRC is very suitable for the universal, ubiquitous, and intelligent electromagnetic terminals in the future world.

2. Results

2.1. Encryption and Decryption of Wireless Secure Communication on the DPM Aperture

We suppose that a signal \( I(t) \) is carried by a plane wave \( e^{i\omega t} \) with a propagation vector \( k \), and the arrival signal at the reference unit of DPM is \( s(t) = I(t)e^{i\omega t} \). Then, the arrival signal at the \( m \)th unit of DPM is expressed as

\[
\begin{align*}
    s_m(t) &= I(t) + \frac{\rho_m}{|k|} \Gamma_m e^{i(\theta + \rho_m)k} \\

\end{align*}
\]

where \( k = k_0 [\sin \theta \cos \varphi, \sin \theta \sin \varphi]^T \) and \( \rho_m = [x_m, y_m]^T \), and \( x_m \) and \( y_m \) are coordinates of the \( m \)th unit of DPM. For a narrowband signal whose bandwidth is \( B \), we have \( \rho_m = \frac{s_m}{|k|} \ll \frac{1}{B} \), and hence \( s_m(t) \approx I(t)e^{i(\theta + \rho_m)k} \). If the reflection or transmission coefficient of the \( m \)th unit is \( \Gamma_m \), then the observation field at a point that is \( r_m \) away from the unit is

\[
O_m(t) = \frac{e^{-j2\pi r_m}}{4\pi r_m} \Gamma_m I(t)e^{i(\theta + \rho_m)k} \tag{2}
\]

Taking contributions of all \( M \) units into consideration, the total signal at the observation point is written as

\[
\begin{align*}
    (\theta, \varphi, t) &= \xi(t)a(\theta, \varphi)I(t)e^{i\omega t} \\

\end{align*}
\]

where \( \xi(t) = [\Gamma_1e^{-j2\theta_1}/4\pi r_1, \Gamma_1e^{-j2\theta_2}/4\pi r_2, \ldots, \Gamma_m e^{-j2\theta_m}/4\pi r_M]^T \), and \( a(\theta, \varphi) = [a_1^m, a_2^m, \ldots, a_M^m]^T \). If we define the transfer function of DPM as \( h(t) = \xi^*(t)a(\theta, \varphi) \), the observation field is then expressed by

\[
\begin{align*}
    u(\theta, \varphi, t) &= h(\theta, \varphi; t)s(t) \\

\end{align*}
\]

This equation shows that the incident signal is modulated by the transfer function of DPM. The previous analyses are developed for the receiving process, but the same transfer function can be used when DPM is used in the transmitting process. Explicit expression of the transfer function is given in Supporting Information Note 2.

From the point of wireless communication, DPM has actually become a part of the communication channel. Particularly, this part is reprogrammable, hence making DPM a very suitable technology for the secure communications. Figure 2a gives a schematic diagram of the DPM-based secure communications. By designing the space-time transfer function \( h(\theta, \varphi, t) \), the source signals are modulated spatially and temporally when they are passing through a DPM. In the time domain, DPM exerts the phase modulations on the source signals; in the space domain, DPM steers the radiation energy to a specified direction. As a result, the source signals are encrypted in both space and time domains. For decryption, the other DPM with the conjugate transfer function \( h^*(\theta, \varphi, t) \) is used to recover the encrypted signals. As an example, the DPM-based encryption and decryption of the phase-modulated signals are simulated. The structure of DPM is demonstrated in Supporting Information Note 1. In a previous work, we have shown that the presented DPM is insensitive to incident angle; hence, the DPM can properly receive the decrypted signals from different directions. Assuming that a source signal is used to modulate the DPM, Figure 2b shows the hypothetical source signal which contains four phase sates \( (0^\circ, 90^\circ, 180^\circ, \text{and} 270^\circ) \). By synthesizing the aperture codes of DPM, the source signals are radiated through directional beam with extra phase shifts \( (72.64^\circ, -19.75^\circ, 252.7^\circ, \text{and} 160^\circ) \), as shown in Figure 2c. The values of such phase shifts are calculated at the point that is \( 2 \) m away from the DPM. The encrypted signals calculated at the same point are shown in Figure 2d. It is observed that the phase difference between every symbol is near zero, hence the effective information has been concealed. The decryption is performed by using the other DPM with conjugate phase shifts \( (72.64^\circ, 160^\circ, 252.7^\circ, \text{and} -19.75^\circ) \). Figure 2e displays the decrypted signals that are consistent with source signal completely. The digital codes of the DPM used for encryption and decryption are given in Supporting Information Note 3.

In the previous analyses, each bit of the original signal is encrypted by one set of the aperture code of DPM. In fact, each single bit can be encrypted by a series of aperture codes to enhance the security. This encryption process is actually an
essential characteristic of code division multiple access (CDMA) technology, which was proposed at first as a secure technology in the military communications, indicating that DPM can be used to realize the CDMA communications. More importantly, the proposed DPM-based secure communications possess significant advantages, namely that the DPM serves as an independent plug-and-play module and can be modified or updated arbitrarily in different scenarios without any changes of the original system, thus saving plenty of time and cost.

2.2. Range Profile Imaging of Multiple Targets by Using DPM-Based Biphase-Coded Signals

As DPMs can implement phase modulations on the aperture, they can be used to produce biphase-coded signals for range profile imaging. Supposing that a carrier wave $\phi^\text{int}$ is modulated by a DPM whose transfer function contains a phase-modulation term, and then the transmitted signal of the DPM can be written as

$$g_t(t) = h(t)\phi^\text{int}$$

where $\phi(t)$ is the binary phase-modulation term expressed as

$$\phi(t) = \begin{cases} \pi \sum_{k=0}^{N-1} c_k \text{rect} \left( \frac{t - k\tau_0 - \tau_0}{\tau_0} \right) & 0 < t < N\tau_0 \\ 0 & \text{else} \end{cases}$$

where $N$ and $\tau_0$ are the length of biphase-coded signals and period of each code, respectively, and $c_k$ is the binary code taking the value of 0 or 1.

Assuming that the receiver is placed at the same position of the transmitter, and then the signal received from a target that is $R$ away from the receiver is

$$g_r(t) = g_t\left( t - \frac{2R}{c} \right)$$

Using the correlation reception for the received signal, we can obtain the range profile imaging of the target

$$\text{Corr}(\Delta t) = g_r\left( t - \frac{2R}{c} \right) \ast g_t^*(t)$$

Figure 2. The DPM-based secure wireless communications. a) Schematic diagram. b) The original signal. c) The phase modulation realized by DPM. d) The encrypted signal. e) The decrypted signal.
where $\Delta t$ is the imaging range. It is clear that the correlation coefficient reaches the maximum when $\Delta t = 2R/c$.

Figure 3 shows an example of the DPM-based range profile imaging. The $M$-sequence with a sequence length of 255 is used to set the values of $c_k$, and two aperture codes corresponding to the binary values of $c_k$ are adopted to configure the DPM. At the point that is 2 m straight ahead of DPM, the calculated radiation phase is $-19.75^\circ$ when $c_k = 0$, and is $160^\circ$ when $c_k = 1$. By switching the two aperture codes according to the $M$-sequence, DPM can generate the specified biphase-coded signal. The switching speed of the aperture codes is defined as 10 MHz and the sampling rate of the received signal is defined as 20 GSa s$^{-1}$.

Supposing that a target is placed in front of the transceiver by a distance of 2 m, the echo signal can be obtained by matched filtering, as shown in Figure 3b. Figure 3c is the calculated range profile of the target. A peak is observed at 1.995 m, which is very close to the defined distance, thus verifying the effectiveness of the proposed DPM-based range profile imaging.

2.3. Realizing Radar Detection and Wireless Communication Independently and Simultaneously

JRC has been an important content of the future information systems and networks. In the term of implementation, the multiplexing forms of JRC include time division, frequency division, code division, and space division. Among these forms, the time division multiplexing is easy to realize but the switching time of functions between radar and communication limits the real-time performance. The frequency division multiplexing and code division multiplexing possess efficient time-frequency resource utilization, and the functions of radar and communication can exist simultaneously. The space division multiplexing can use directional beams pointing at different directions to implement the radar and communication independently. In practice, the space division multiplexing is usually combined with other kinds of multiplexing forms because the communication users and radar targets are generally distributed in different spatial regions.
Given that DPMs can manipulate the electromagnetic waves in the space, time, and frequency domains, they can be used to realize various multiplexing forms. Figure 4a shows a schematic diagram of the DPM-based JRC, in which the DPM produces two-directional beams with the modulated phases. The two beams will form two independent channels, which are used to communicate with the cooperate user and to detect the non-cooperate target, respectively. The phase-modulated signals carried by the two channels can be either different signals, or the same signal shared by the radar and communication systems.

For demonstration, the DPM is configured to produce two-directional beams pointing to the elevation angles of 10° and −30°, respectively. Based on the previous analyses, the aperture codes for such two-directional beams with independent radiation phases can be calculated. The radiation phases of each beam possess four-phase states. Consequently, 16 sets of aperture codes are needed for independent quadrature-phase modulations of the two-directional beams. These aperture codes are given in Supporting Information Note 4. Figure 4b–e gives the simulated far-field patterns by keeping the phase of the first beam (10°) unchanged and changing the phase of the second beam (−30°) by an increment of 90°. Figure 5 shows the measured results of the radiation patterns and phases. It is observed that the phase modulations will not change the directions of the directional beams, and the phase modulations of each directional beam can be modulated independently. Hence, the DPM provides a flexible method to realize the space, time, frequency, and code division multiplexing technologies in either unique or hybrid ways. This function forms the basis of the DPM-based JRC.

At the foundation of aforementioned simulations and measurements, we build a DPM-based JRC, and Figure 6a shows a photograph of the system and testing environment. The DPM is illuminated by a single-frequency wave (28 GHz). By designing the adequate aperture codes, the DPM will produce two-directional beams with elevation angles of 20° and −20°.
hence forming two spatial channels. The first channel (θ = 20°) is used to detect a metal plate, which is 2.5 m away from the DPM, in which a horn antenna placed close to DPM serves as a radar receiver. The second channel (θ = 20°) is used to implement the wireless communication, in which the other horn antenna that is 1.42 m away from DPM serves as a communication receiver. The

Figure 5. Measured results of two-directional beams with independent radiation phases. a–d) The measured radiation patterns. e–h) The measured radiation phases, in which ϕ₁ and ϕ₂ are phase modulation terms of the two beams, respectively.
Signals received in the two channels are input to an oscilloscope (Keysight, MSOS804A) through a frequency converter, which has two transmitting channels and two receiving channels. Theoretically, the signals in each channel can be designed independently. In this experiment, the $M$-sequence is used in both channels for simplicity. In contrast, the $M$-sequences in the two channels are time synchronized, and hence can be used to obtain the relative time delay of the two channels. Normally, coherent transceiver is needed to measure the absolute time delay of the transceiver signal in the radar channel, so that the distance of the target can be detected. However, realizing such a system is expensive, time consuming, and labor consuming. Instead, we can measure the relative time delay of the two channels, from which the distance of the radar target can also be obtained if we know the distance of the communication receive in advance. It is noted that this procedure actually provides an indirect DPM-based method to detect the distance of radar targets.

The down-converted signals of the two channels are sampled by an oscilloscope at 1.5 GHz with a sampling rate of 20 GSa s$^{-1}$. The coding rate of the $M$-sequence is 10 MHz, which is also the switching speed of the DPM. The resolution of range detection can be calculated as $c\tau_c/2$, where $c$ is speed of light and $\tau_c$ is pulse width. The calculated value is 15 m. Figure 6b,d displays the sampled signals of the two channels. Due to the inconsistency of radiation intensities while switching the aperture codes, the amplitudes of different symbols are unequal. Nevertheless, the envelope of the signals indicates that the carrier waves have been modulated by the $M$-sequence. Fluctuations of the envelope can be eliminated by auto gain control (AGC), which have been commonly used in the electronic and information systems.

Figure 6. Experiment of the DPM-based JRC. Measured results of the received radar and communication signals. a) Photograph of the DPM-based JRC and testing environment. b) The sampled signals from the communication channel. c) The communication signals after matched filtering. d) The sampled signals from the radar channel. e) The relative range profile imaging of the radar target.
3. Conclusion

Compared with binary DPM, multi-bit DPM has smaller discrete error than that of binary DPM. Correspondingly, they can improve bit error rate of wireless communication and enhance precision of range detection. However, multi-bit DPM needs much more complex DC feeding network, which decreases the flexibility and convenience of the DPM-based JRC. A trade-off between performance and realizability has to be considered. Beam alignment and polarization consistence are other considerations when we apply the presented DPM-based JRC. Because the DPM-based signals are included within the scope of main lobe, the transmitter and the receiver have to align the main lobes so that the signals can be properly transmitted and received. Also, polarizations of the transmitter and the receiver need to be consistent, since the presented DPM is linearly polarized. In complex electromagnetic environment, polarization of transmission signals is very likely to be altered. Two methods can be used to deal with this problem. The first method is designing dual-polarized unit cell for the digital metasurface; the second method is using two orthogonally polarized metasurfaces for both transmitter and receiver. In such ways, the system can process signals with dual polarizations.

In summary, this work established a DPM-based mechanism to realize an efficient JRC system, which implements the spatial and time-frequency modulations directly on the DPM aperture, and hence greatly simplified the architecture and reduced the cost of the system. For demonstration, this work has designed three examples including the encryption and decryption of wireless communications, range profile imaging, and simultaneous radar detection and wireless communications. These functions have been well verified by simulations and experiments, thus showing significant potentials of the DPM-based JRC to be a universal, ubiquitous, and intelligent electromagnetic terminal in the future world.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

X.W. conducted the analytical modeling, numerical simulations, designs, and measurements. Z.A.H. conducted parts of the numerical simulations and measurements. J.W.W., B.Y.L., and W.H.W. conducted parts of measurements. W.X. and T.J.C. coordinated and supervised the work, and contributed to the preparation and writing of the manuscript.

Data Availability Statement

The data that support the findings of this study are available in the Supporting Information of this article.

Keywords

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Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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