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Comparative Analysis of Digital Self-Interference Cancellation Methods for Simultaneous Transmit and Receive Arrays

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Abstract: This paper provides a comprehensive theoretical derivation of the residual noise power and effective isotropic isolation (EII) signal models in baseband digital cancellation, aperture-level digital cancellation, and beamforming spatial cancellation models in simultaneous transmit and receive (STAR) arrays. We simulated and analyzed the isolation performance and self-interference (SI) noise cancellation of STAR systems using digital SI cancellation (SIC) and beamforming in a 32-element planar array. The simulation results show that in the absence of SIC or baseband digital SIC, the EII obtained by receive adaptive beamforming (ABF) is 20 dB higher than that obtained by transmit ABF. On the basis of aperture-level digital SIC, the EII obtained from transmit ABF and receive ABF is basically the same. The EII obtained by baseband digital SIC is 22.5 dB and 41.1 dB lower than that of transmit ABF and receive ABF, respectively. Therefore, baseband digital SIC technology is not required when using transmit ABF and receive ABF.

Keywords: baseband digital cancellation; aperture-level digital cancellation; beamforming airspace cancellation; residual noise power; effective isotropic isolation



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1. Introduction

In traditional communication systems, the transceiver is time-sharing; that is, the same antenna or set of antennas is used to send and receive signals at different times. However, with the increasing demand for communications and the finite nature of spectrum resources, simultaneous transmit and receive (STAR) technology has emerged, allowing simultaneous transmit and receive operations to be performed in the same frequency band at the same time in the same time period. In wireless communication systems [1], the transceiver technology can improve spectral efficiency and reduce latency and is suitable for high-speed data transmission and multi-user communication scenarios. In radar systems [2,3], the simultaneous transceiver technology can improve target detection performance and anti-jamming ability. In the field of satellite communications [4], the simultaneous transmission and reception technology can improve the communication capacity and coverage of satellite systems. In cognitive electronic warfare [5,6], STAR can adapt to the agility of enemy radar in various time, frequency, and air domains. STAR will introduce the problem of self-interference (SI) between the self-transmitted signal and the received signal, which needs to be solved by effective SI cancellation technology. Most of the literature uses adaptive filtering [7], spatial cancellation [8], digital signal processing [9], polarization domain processing [10], time domain processing [11], and code domain processing [12] to achieve SI cancellation (SIC).

SIC is the primary technique used by most STAR systems to mitigate SI, which combines a filtered copy of the interfering signal with the received signal in order to achieve

SI cancellation through destructive interference. Generally, it includes a propagation domain, analog domain, and digital domain SIC. The baseband digital SIC in digital SIC is achieved by processing the received signal at the receive end, estimating the signal sent by the transmit end at the receive end, and eliminating it from the received signal. This can effectively reduce or eliminate the impact of SI and improve the performance of the STAR system. Usually, adaptive filters [13,14] (such as the LMS (Least Mean Square) algorithm or RLS (Recursive Least Squares) algorithm) are used for the implementation. The use of adaptive filters in baseband digital SI cancellation can effectively improve the performance and reliability of STAR systems. But it is also necessary to consider issues such as computational complexity [15], system stability [16], and parameter selection [17]. In practical applications, it is necessary to comprehensively consider various factors and choose appropriate adaptive filter methods and parameter settings to achieve the best SIC effect.

The aperture-level STAR digital SIC system [18,19] proposed by the Massachusetts Institute of Technology (MIT) is a solution to SI problems in simultaneous transmission and reception communication. Compared to traditional digital SIC, this system utilizes adaptive digital signal processing technology and deploys independent adaptive filters on each antenna of the antenna array to achieve more precise and accurate SIC, thus improving the system's SIC performance and communication quality [20]. On the basis of the aperture-level STAR system, the team studied beamforming optimization based on information theory and neural networks [21,22], array partitioning optimization based on information theory and genetic algorithms to improve the isolation performance of the system [23,24], and then the impact of high-power transmission signals on the isolation performance of the aperture-level STAR system [25]. Other scholars have also explored the spatial coupling path characteristics of the transmit and receive links in the transmit array and receive array [26,27], proposed an aperture-level SIC method based on pure phase beamforming [28], and proposed a beamforming optimization method that minimizes the SI power on each receive antenna for SIC [29]. Further, MIT also researched STAR phased-array implementations that could be used to create simultaneous multifunction systems [30,31]. The aperture-level STAR system requires complex signal processing algorithms and hardware implementation, but it can effectively solve the SI problem in simultaneous transmission and reception communication and improve system performance.

The spatial cancellation based on beamforming is achieved by beamforming the received signal in the spatial domain to suppress SI signals. By adjusting the beam direction and shape of the antenna array [32–35], SI signals are suppressed in specific directions. But its suppression performance is limited by spatial resolution and beamforming accuracy. This is suitable for scenarios that require signal suppression in the spatial domain, such as communication systems in multipath interference environments.

The accuracy of the SIC system determines the degree to which the cancellation channel simulates the SI coupling channel, thereby establishing the maximum level of achievable cancellation. The dynamic range of the SIC system determines the amount of additional noise or distortion generated by the SI power processing and the system itself. Finally, the efficiency of the SIC system characterizes the additional losses introduced in the transmission and/or reception signal paths due to the implementation of SIC. Although residual SI caused by limited accuracy can be removed in principle through subsequent elimination stages, damage caused by reduced efficiency and limited dynamic range is often difficult or impossible to repair. Developing effective SIC for phased arrays requires considering all these design factors coupled with the diversity of transmit and receive channels that interact in complex coupled environments.

This paper further analyzes and compares the isolation performance and SIC of STAR systems using baseband digital cancellation, aperture-level digital cancellation, and adaptive beamforming (ABF). Through simulation verification, it is found that the suppression of SI by receive ABF is greater than that of transmit ABF on the basis of no SIC or baseband digital SIC. On the basis of aperture-level digital SIC, the cancellation

effect of receive ABF is consistent with that of transmit ABF. The cancellation effect of only transmit ABF or only receive ABF is better than that of only performing baseband digital SIC cancellation. On the basis of baseband digital SIC, the suppression of SI by receive ABF is greater than that of transmit ABF. The STAR array model discussed in this article is more fundamental and involves mathematical calculations of theoretical values. The research results can provide basic theoretical support for specific SIC technology research.

The paper is organized as follows. In Section 2, we describe the baseband digital cancellation, aperture-level digital cancellation, and beamforming spatial cancellation models in the STAR array and derive the residual noise power and EII of the three models in detail. Section 3 analyzes the isolation performance of digital SIC, beamforming, and SI noise cancellation for STAR systems. Finally, the conclusion is provided in Section 4.

2. Digital SIC for Simultaneous Transmit and Receive

We described a simple signal model to describe the signal and noise components in the STAR array, as shown in Figure 1. Assuming the channel is a linear, narrowband, additive white Gaussian noise (AWGN) channel to reduce the complexity of the analysis, external signals of interest are not considered here. Table 1 shows the symbols and definitions of signals in the STAR model.

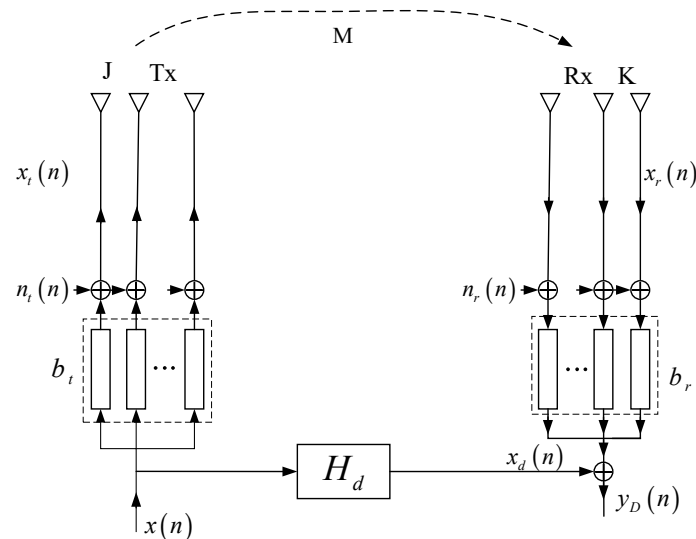


Figure 1. The STAR signal model for baseband digital SIC.

Table 1. The symbols and definitions of signals in the STAR model.

Symbol	Definition
$x(n)$	Digital baseband signal
b_t	Transmit beamforming
$n_t(n)$	Transmit noise
$x_t(n)$	Transmit signal
M	Coupling matrix
$x_r(n)$	Receive signal
$n_r(n)$	Receive noise
b_r	Receive beamforming
$y(n)$	Receive signal after SIC

The symbol $x(n) \in \mathbb{C}$ is the expected signal transmitted and is assumed to be $E[|x(n)|^2] = 1$. $b_t \in \mathbb{C}^{J \times 1}$ is the beamforming vector for transmission, with a total

transmission power of $P_t = b_t^H b_t$. The covariance matrix $n_t(n)$ of transmitter noise $N_t \triangleq E[n_t(n)n_t^H(n)]$. In the (θ_t, ϕ_t) direction, the EIRP of the far-field transmission beam is

$$EIRP(\theta_t, \phi_t) = g(\theta_t, \phi_t) b_t^H q_t(\theta_t, \phi_t) q_t^H(\theta_t, \phi_t) b_t, \quad (1)$$

Assuming that the antenna gain is consistent for all elements. It is the far-field guidance vector of the beam in the direction of a planar array

$$q_t(\theta_t, \phi_t) = \exp \left[-j \frac{2\pi}{\lambda} (x_t \cos(\phi_t) \sin(\theta_t) + y_t \sin(\phi_t) \sin(\theta_t)) \right], \quad (2)$$

where x_t and y_t are the positions of each transmit antenna element on the x -axis and y -axis of the array plane, respectively.

At the receive end, the incident signal of each receive element is $x_r(n) \in \mathbb{C}^{K \times 1}$.

$$\begin{aligned} x_r(n) &= M x_t(n) \\ &= M(b_t \cdot x(n) + n_t(n)), \end{aligned} \quad (3)$$

where M is the mutual coupling matrix between the transmit and receive elements. The received signal from each channel is used for receive beamforming.

$$y(n) = b_r^H [M x_t(n) + n_r(n)], \quad (4)$$

where $b_r \in \mathbb{C}^{K \times 1}$ is the receive beamforming vector and $b_r^H b_r = 1$. $n_r(n)$ is the receiver noise, with its covariance matrix $N_r \triangleq E[n_r(n)n_r^H(n)]$. In the (θ_r, ϕ_r) direction, the gain of the receive array on the far-field incident signal is

$$G_r(\theta_r, \phi_r) = g(\theta_r, \phi_r) b_r^H q_r(\theta_r, \phi_r) q_r^H(\theta_r, \phi_r) b_r, \quad (5)$$

where $q_r(\theta_r, \phi_r)$ is the far-field guidance vector of the beam in the (θ_r, ϕ_r) direction. For a planar array,

$$q_r(\theta_r, \phi_r) = \exp \left[-j \frac{2\pi}{\lambda} (x_r \cos(\phi_r) \sin(\theta_r) + y_r \sin(\phi_r) \sin(\theta_r)) \right], \quad (6)$$

For directional systems, the effective isotropic isolation (EII) can be expressed as the ratio of EIRP to Effective Isotropic Sensitivity (EIS),

$$EII = \frac{EIRP}{EIS}, \quad (7)$$

where the $EIRP = P_t G_t$, $EIS = P_n / G_r$. Therefore,

$$EII = \frac{P_t \cdot G_t}{P_n / G_r} = \frac{P_t}{P_n} \cdot G_t G_r, \quad (8)$$

where the total power of SI and noise is $P_n = P_X + P_{NT} + P_{NR}^x + P_{NR}^{nt} + \sigma_{nr}^2$. Among them, $P_X = b_r^H M b_t b_t^H M^H b_r$ is the SI power generated by the transmission signal $x_t(n)$, $P_{NT} = b_r^H M N_t M^H b_r$ is the SI power generated by the transmitter noise, and $P_{NR} = b_r^H N_r b_r$ is the total noise power of the receiver. The covariance matrices for transmit and receive noise are $N_t = \eta_t^{-1} \text{Diag}(b_t b_t^H)$ and $N_r = \eta_r^{-1} \text{Diag}(E[x_r x_r^H]) + \sigma_{nr}^2 I$, respectively. η_t and η_r are the maximum signal-to-noise ratios of the transmit and receive channels under high-power excitation, respectively. The σ_{nr}^2 is the receiver thermal noise power under low-power excitation.

2.1. Baseband Digital SIC

The baseband digital SIC [36] uses a digital filter to combine the transmitted baseband signal with the digital received signal to achieve SIC. The signal model is shown in Figure 1, and the cancellation signal at the receive end $y_D(n)$ can be represented as

$$\begin{aligned}
 y_D(n) &= b_r^H(x_r(n) + n_r(n)) + x_d(n) \\
 &= b_r^H(Mx_t(n) + n_r(n)) + H_d x(n) \\
 &= b_r^H M b_t x(n) + b_r^H M n_t(n) + b_r^H n_r(n) + H_d x(n) \\
 \Rightarrow P_X &= (b_r^H M b_t + H_d)^2 = b_r^H M b_t b_t^H M^H b_r + H_d b_t b_t^H H_d^H \\
 P_{NT} &= \eta_r^{-1} b_r^H M \text{Diag}(b_t b_t^H) M^H b_r \\
 P_{NR}^x &= \eta_r^{-1} b_r^H \text{Diag}[M b_t b_t^H M^H] b_r \\
 P_{NR}^{nt} &= \eta_r^{-1} \eta_t^{-1} b_r^H \text{Diag}[M \text{Diag}(b_t b_t^H) M^H] b_r
 \end{aligned} \tag{9}$$

By adjusting the coefficient of the filter H_d when $H_d \rightarrow b_r^H M b_t$ occurs, the SI generated by the transmit signal $x_t(n)$ can be completely canceled out, and an adaptive digital filtering algorithm with any number of taps can usually be used to achieve this. The total interference and noise power of $y_D(n)$ is

$$P_n = P_{NT} + P_{NR}^x + P_{NR}^{nt} + \sigma_{nr}^2 \tag{10}$$

where the SI power caused by transmit noise P_{NT} is $\eta_t^{-1} b_r^H M \text{Diag}(b_t b_t^H) M^H b_r$. The increase in receive noise caused by high-power transmit signals P_{NR}^x is $\eta_r^{-1} b_r^H \text{Diag}[M b_t b_t^H M^H] b_r$. The increase in receive noise caused by high-power transmit noise P_{NR}^{nt} is $\eta_r^{-1} \eta_t^{-1} b_r^H \text{Diag}[M \text{Diag}(b_t b_t^H) M^H] b_r$. The baseband digital SIC cannot cancel out the noise power P_{NT} of the transmit channel, and it cannot alleviate the impact of limited receiver dynamic ranges P_{NR}^x and P_{NR}^{nt} under high-power SI. It can be further concluded that the EII after the baseband digital SIC is

$$EII = \frac{P_t}{P_n} \cdot G_t G_r = \frac{P_t}{P_{NT} + P_{NR}^x + P_{NR}^{nt} + \sigma_{nr}^2} \cdot G_t G_r, \tag{11}$$

As can be seen from Equation (3), the baseband digital SIC can only cancel out the SI term generated by the transmitted signal but cannot cancel out the rest of the SI terms. In the digital SIC, the adaptive filtering algorithm can be used to compensate for the dynamic changes in the coupling and scattering environment in real time.

2.2. Aperture-Level Digital SIC

The digital SIC provides high accuracy, efficiency, and bandwidth, but the reference signal for baseband digital cancellation is derived from the digital baseband, which does not contain transmit noise information and cannot eliminate the SI component caused by the transmit noise.

In order to overcome this problem, the aperture-level digital SIC [19] introduces the observation link to measure and digitize the transmit signal, and by extracting the copy signal from the output of the PA to form an offset signal through the observation link, and canceling the SI signal at the output of the receive beamforming, the introduction of the observation link can not only cancel the SI component caused by the transmit signal but also further cancel out the SI component caused by the transmit noise. As shown in the signal model in Figure 2, the observed signal $x_o(n) \in \mathbb{C}^{J \times 1}$ in the aperture-level STAR digital SIC array is

$$x_o(n) = b_c^H H_o(x_t(n) + n_o(n)). \tag{12}$$

where $H_o \in \mathbb{C}^{J \times J}$ represents the diagonal matrix of signal attenuation for each transmit channel, $n_o(n)$ is the additive Gaussian white noise due to the limited dynamic range of the observed channel, and $N_o \triangleq E[n_o n_o^H] = \eta_o^{-1} \text{Diag}(b_t b_t^H)$ is its noise covariance matrix.

The $x_o(n)$ is passed through a multi-channel digital filter $b_c \in \mathbb{C}^{J \times 1}$ and then combined with the received signal to obtain the receiver cancellation signal $y_{AL-D}(n)$.

$$\begin{aligned}
 y_{AL-D}(n) &= b_r^H [x_r(n) + n_r(n)] + x_o(n) \\
 &= b_r^H [n_r(n) + Mx_t(n)] + b_c^H H_o x_t(n) + b_c^H H_o n_o(n) \\
 &= b_r^H M b_t x(n) + b_r^H M n_t(n) + b_r^H n_r(n) + b_c^H H_o b_t x(n) + b_c^H H_o n_t(n) + b_c^H H_o n_o(n) \\
 \Rightarrow P_X &= b_r^H M b_t b_t^H M^H b_r + b_r^H H_o b_t b_t^H H_o^H b_r \\
 P_{NT} &= \eta_r^{-1} b_r^H M \text{Diag}(b_t b_t^H) M^H b_r + \eta_r^{-1} b_c^H H_o \text{Diag}(b_t b_t^H) H_o^H b_c \\
 P_{NR}^x &= \eta_r^{-1} b_r^H \text{Diag}[M b_t b_t^H M^H] b_r \\
 P_{NR}^{nt} &= \eta_r^{-1} \eta_t^{-1} b_r^H \text{Diag}[M \text{Diag}(b_t b_t^H) M^H] b_r \\
 P_{NO} &= \eta_o^{-1} b_c^H H_o \text{Diag}(b_t b_t^H) H_o^H b_c
 \end{aligned} \tag{13}$$

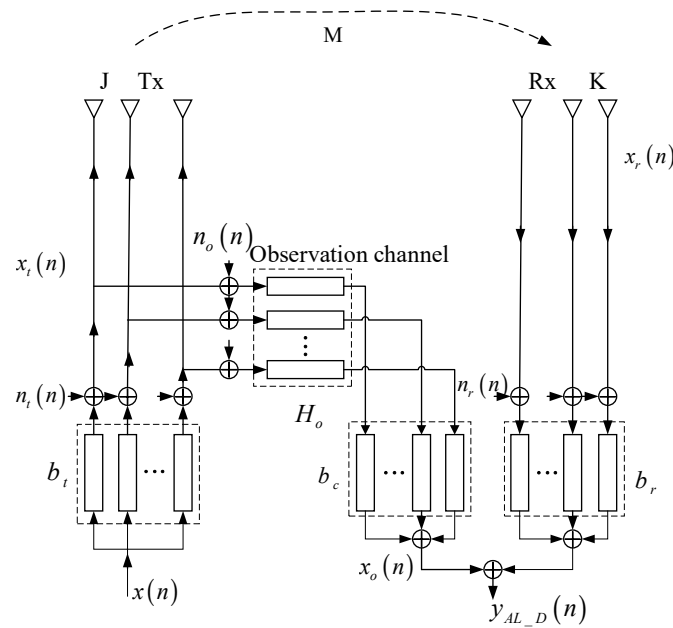


Figure 2. The STAR signal model for aperture-lever digital SIC.

If b_c^H satisfies $b_c^H \rightarrow -b_r^H M H_o^{-1}$, then the SI component generated by $x_t(n)$ will be canceled out and the total power of the residual signal will be

$$P_n = P_{NO} + P_{NR}^x + P_{NR}^{nt} + \sigma_{nr}^2 \tag{14}$$

However, the observed link is equivalent to the receive link; η_o can be replaced by η_r , and the channel noise power P_{NO} of the observed link is expressed as $\eta_r^{-1} b_c^H H_o \text{Diag}(b_t b_t^H) H_o^H b_c$. The received noise caused by the transmitted signal P_{NR}^x is denoted as $\eta_r^{-1} b_r^H \text{Diag}[M b_t b_t^H M^H] b_r$. The received noise caused by the transmit noise P_{NR}^{nt} is denoted as $\eta_r^{-1} \eta_t^{-1} b_r^H \text{Diag}[M \text{Diag}(b_t b_t^H) M^H] b_r$.

Compared with the baseband digital SIC, the aperture-level digital SIC is able to cancel out the SI component P_x generated by the transmitted signal and the SI component P_{NT} generated by the transmitted channel noise at the cost of adding an additional SI component P_{NO} generated by the noise of the observed channel. The EII after the aperture-level digital SIC is

$$EII = \frac{P_t}{P_n} \cdot G_t G_r = \frac{P_t}{P_{NO} + P_{NR}^x + P_{NR}^{nt} + \sigma_{nr}^2} \cdot G_t G_r, \tag{15}$$

In the case that the dynamic range of the observation channel η_o is significantly greater than that of the transmission channel η_t , it is very useful to introduce the observation channel for SIC.

2.3. Spatial Cancellation of Beamforming

STAR arrays can also further improve EII through spatial cancellation [19] by controlling their radiation patterns to mitigate SI. Here the EII is written as follows:

$$EII = P_t G_t(\phi, \theta, b_t) g(\phi, \theta) \frac{b_r^H q_r(\phi, \theta) q_r^H(\phi, \theta) b_r}{b_r^H M_{br} b_r}, \quad (16)$$

where $b_r^H M_{br} b_r = P_X + P_{NT} + P_{NR}^x + P_{NR}^{nt} + \sigma_{nr}^2$ denotes all noise and interference terms, M_{br} denotes the effective covariance of received interference and noise, and the expansion of M_{br} depends on the specific SIC architecture.

The equation for calculating the EII includes the generalized Rayleigh quotient of the receive beamforming vector b_r . Therefore, it is possible to pass the order

$$b_r \rightarrow \alpha (M_{br})^{-1} q_r(\phi, \theta), \quad (17)$$

which maximizes the EII. The α scalar constant is used to ensure $b_r^H b_r = 1$, and Equation (17) represents the adaptive beamforming method, which is similar to the one used for external interference nulling, and can reduce both SI and external interference. The matrix M_{br} depends on the transmit beamforming, and according to the $a^H \text{Diag}(bb^H)a = b^H \text{Diag}(aa^H)b$ equation, the generalized Rayleigh Quotient of the receive beamforming can also be reconstructed into the generalized Rayleigh Quotient of the transmit beamforming. Therefore, $b_r^H M_{br} b_r$ can be transformed to the $b_t^H M_{bt} b_t$ to give the equation for EII as

$$EII = P_t G_r(\phi, \theta, b_r) g(\phi, \theta) \frac{b_t^H q_t(\phi, \theta) q_t^H(\phi, \theta) b_t}{b_t^H M_{bt} b_t}, \quad (18)$$

From the perspective of a transmit beamforming, M_{br} is similar to a virtual covariance matrix for interference and noise, and its expansion depends on the specific SIC architecture. Similar to the receive beamforming described above, the formula for the transmit beamforming to maximize EII is as follows

$$b_t \rightarrow \beta (M_{bt})^{-1} q_t(\phi, \theta), \quad (19)$$

where the scalar constant β is used to ensure $b_t^H b_t = P_t$. M_{bt} is a function of b_t and can be fixed to optimize the transmit beamforming. M_{bt} is a function of b_r and can be fixed to optimize the receive beamforming. Equations (16) and (18) are solved iteratively, and the residual covariance matrix in each formula is calculated alternately in each iteration to obtain the optimal EII.

3. Results and Discussion

In this section, the aperture-level STAR array model will be simulated and verified. In order to evaluate the SIC performance of the STAR array, the spatial cancellation performance of beamforming, and the performance of the STAR array combined with analog and digital SIC, a 32-element STAR array was used to form a planar phased array, the structure of which is shown in Ref. [9].

The following is a simulation of the STAR phased array composed of the above antenna arrays. The simulation conditions are as follows: the center frequency is 4.3 GHz, the noise figure is 3 dB, the bandwidth is 100 MHz, the transmit power is 1000 W, the thermal noise power of the receiver is -91 dBm, the dynamic range of the transmitter is 45 dB, the dynamic range of the receiver is 70 dB, the dynamic range of the observation link is negligible, the dynamic range of the simulated SIC cancellation link is 80 dB, and the beam scanning angle is $(-70^\circ, 70^\circ)$.

3.1. Performance Analysis of Digital SIC and Adaptive Beamforming

3.1.1. Comparative Analysis of Digital SIC and Adaptive Beamforming

ABF was performed on the basis of baseband digital SIC, and the performance effect of ABF on baseband digital SIC was analyzed. As can be seen from Figure 3a, at a beam scanning angle of 0° , the EII is 72.8 dB without SIC and ABF, 120.5 dB for baseband digital SIC and no ABF, 140.8 dB for transmit ABF under baseband digital SIC, 161.6 dB for receive ABF under baseband digital SIC, and 184.3 dB for transmit and receive ABF under baseband digital SIC. It can be concluded that the cancellation effect of receive ABF on the basis of baseband digital SIC is better than that of transmit ABF on the basis of baseband digital SIC. The residual noise power of each SIC is shown in Figure 3b. The P_n without SIC and ABF is 26.4 dBm at a scan angle of 0° . With the baseband digital SIC, the P_n is reduced by -21.3 dBm. The P_n of baseband digital SIC and ABF is -90.1 dBm, a 0.9 dBm increment in P_n to floor noise. The effect of receive ABF on suppressing P_n is better than transmit ABF, which is -47.7 dBm and -66.7 dBm, respectively.

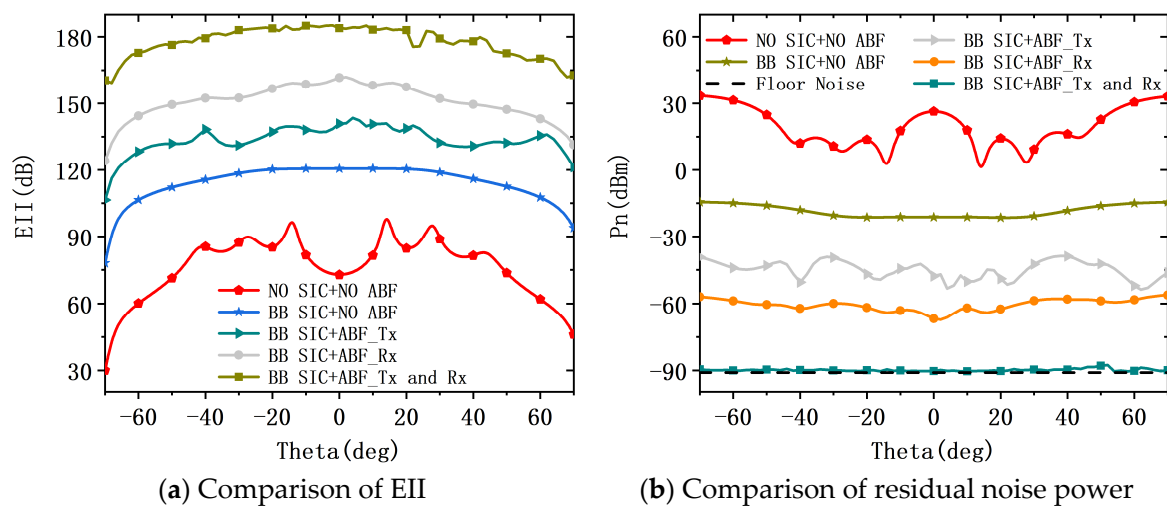


Figure 3. Performance comparison of baseband digital SIC and transmit and receive ABF.

ABF was performed on the basis of aperture-level digital SIC, and the effect of ABF on the performance of baseband digital SIC was analyzed. As can be seen from Figure 4a, at a beam scanning angle of 0° , the EII is 72.8 dB without SIC and ABF, 143 dB for aperture-level digital SIC and no ABF, 164.2 dB for transmit ABF under aperture-level digital SIC, 163.9 dB for receive ABF under aperture-level digital SIC, and 185.8 dB for transmit and receive ABF under aperture-level digital SIC. It can be concluded that the cancellation effect of receive ABF on the basis of aperture-level digital SIC is consistent with that of transmit ABF. The residual noise power of each SIC is shown in Figure 4b. Using aperture-level digital SIC, P_n decreased by -43.2 dBm at a scan angle of 0° . The P_n of the aperture-level digital SIC and ABF is -90.3 dBm, and the increment of P_n with the base noise is 0.7 dBm. The suppression of P_n by transmit ABF and receive ABF is the same, and compared to aperture-level digital SIC, the suppression of P_n has increased by 36 dBm.

The system isolation performance of ABF is made on the basis of not performing SIC. As can be seen from Figure 5a, at a beam scanning angle of 0° , the EII is 72.8 dB without SIC and ABF, 143 dB for transmit ABF without SIC, 161.6 dB for receive ABF without SIC, and 183.8 dB for transmit and receive ABF without SIC. It can be concluded that the offsetting effect of receive ABF on the basis of no SIC is better than that of transmit ABF. Figure 5b shows that the residual noise is consistent with the change in EII at a scan angle of 0° . The P_n of no SIC and transmit ABF, no SIC and receive ABF are -47.8 dBm and -66.6 dBm, respectively.

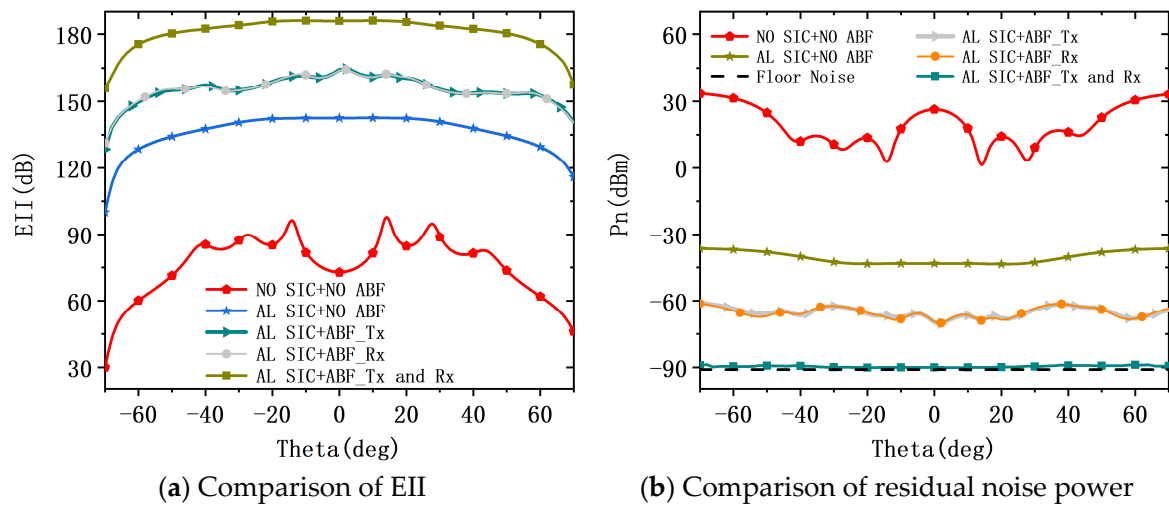


Figure 4. Performance comparison of aperture-level digital SIC and transmit and receive ABF.

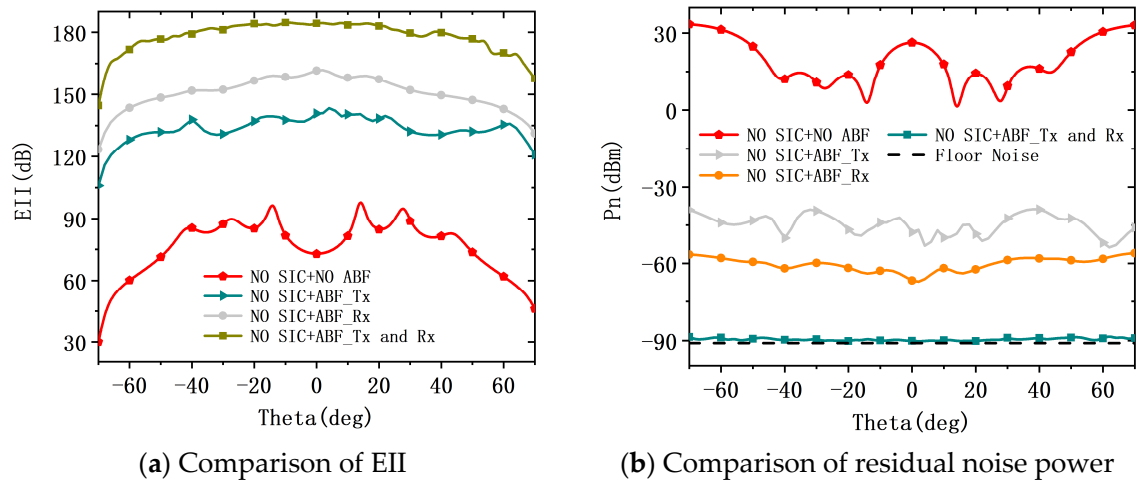


Figure 5. Performance comparison of no SIC and transmit and receive ABF.

As can be seen from Figures 3a, 4a and 5a, at a beam scanning angle of 0° , the transmit ABF and receive ABF EII without SIC are 22.5 dB and 40.5 dB higher than those for baseband digital SIC and ABF, respectively. The EII without SIC and transmit ABF is the same as the aperture-level digital SIC and the EII without ABF, with the EII without SIC and receive ABF being 18.6 dB more than the aperture-level digital SIC and the EII without ABF. In the absence of SIC, baseband digital SIC and aperture-level digital SIC, the EII obtained when transmit and receive ABF can exceed 180 dB, which illustrates the superiority of the ABF offsetting effect.

3.1.2. Comparative Analysis of Transmit and Receive ABF

In the case of no SIC, baseband digital SIC, and aperture-level digital SIC, the isolation and residual noise power of transmit and receive ABF are compared. Figure 6a shows that the EII of transmit ABF without SIC is basically the same as that of transmit ABF in the case of baseband digital SIC, and the EII of both cases is 67.7 dB higher than that of EII without SIC and ABF. It can be concluded that if the transmit ABF is performed, there is no need to perform the baseband digital SIC. In the case of aperture-level digital SIC, the EII of transmit ABF is 20 dB more than in the previous two cases. In the three cases, the EII of transmit ABF alone was 43 dB, 43.5 dB, and 21.6 dB lower than that transmit and receive ABF, respectively. Figure 6b shows that the residual noise is consistent with the change in EII at a scan angle of 0° . The suppression of P_n by no SIC and transmit ABF, baseband

digital SIC, and transmit ABF is the same; the P_n are 47.7 dBm. The P_n of aperture-level digital SIC and transmit ABF is -69.8 dBm, which is an increment of 22 dBm compared to the first two.

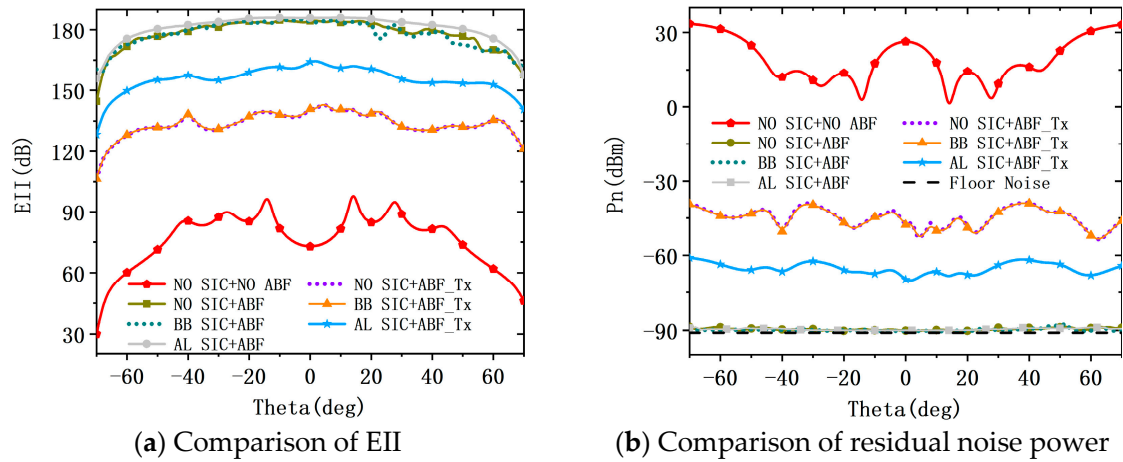


Figure 6. Performance comparison of digital SIC and transmit ABF.

In the case of no SIC, baseband digital SIC, and aperture-level digital SIC, the isolation and residual noise power of only receiving ABF and transmit and receive ABF are compared. Figure 7a shows that the EII of receive ABF without SIC is basically the same as that of receive ABF in the case of baseband digital SIC, at a beam scanning angle of 0° , but the EII in both cases is 88.6 dB higher than that of receive ABF without SIC and without ABF. It can be concluded that if you do receive ABF, you do not need to perform baseband digital SIC. In the case of aperture-level digital SIC, the EII of receive ABF is only 2.3 dB more than in the previous two cases. In the three cases, the EII of transmit ABF alone was 22.2 dB, 22.7 dB, and 21.6 dB lower than that of transmit and receive ABF, respectively. Figure 7 shows that the residual noise is consistent with the change in EII at a scan angle of 0° . The P_n of aperture-level digital SIC and receive ABF is -69.5 dBm, which is an increment of 3 dBm compared to the no SIC and receive ABF, baseband digital SIC and receive ABF.

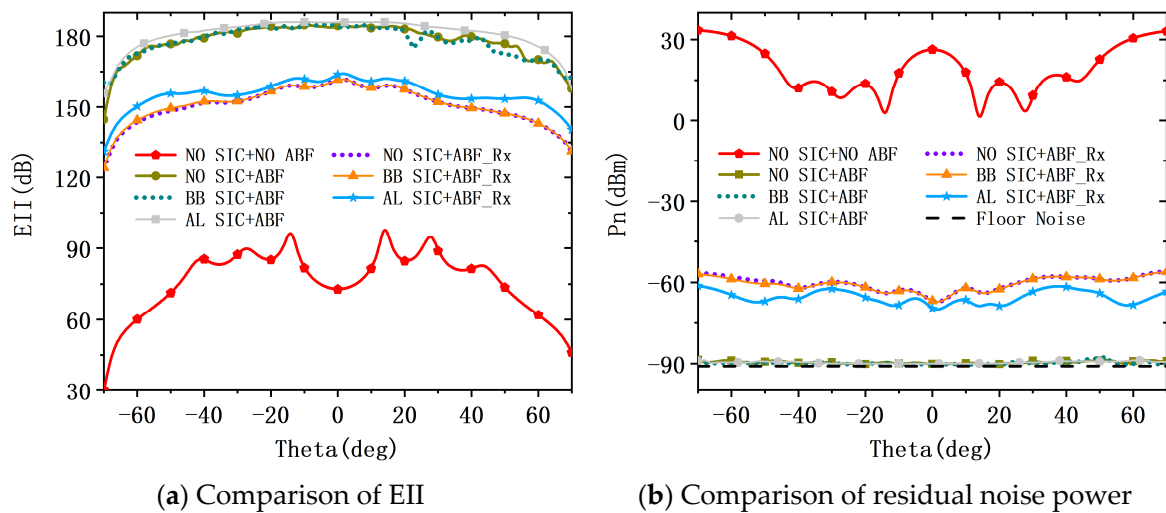


Figure 7. Performance comparison of digital SIC and received ABF.

Table 2 shows the EII table obtained by digital SIC and ABF technology, and it can be seen from the above analysis that in the absence of SIC and baseband SCI, the offset effect of transmit ABF is worse than that of receive ABF, but the difference in EII between transmit and receive ABF is relatively small. The effect of transmit ABF or receive ABF on the basis of aperture-level digital SIC is basically the same. The EII of transmit and receive ABF based on the aperture-level digital SIC is 1.5 dB higher than that of transmit and receive ABF based on the baseband digital SIC. The EII of transmit and receive ABF under baseband digital SIC is 0.5 dB higher than that of transmit and receive ABF without SIC.

Table 2. EII comparison between digital SIC and ABF.

Digital SIC	No ABF	Transmit ABF	Receive ABF	Transmit and Receive ABF
No SIC	72.8 dB	140.8 dB	161.6 dB	183.8 dB
Baseband SIC	120.5 dB	141.5 dB	161.9 dB	184.3 dB
Aperture-level SIC	142.5 dB	163.9 dB	164.2 dB	185.8 dB

3.2. Residual Self-Interference Analysis

This subsection analyzes the SICs in the case of transmit and receive ABF only, baseband digital SIC only, aperture-level digital SIC only, and both SIC and ABF.

3.2.1. Comparative Analysis of Digital SIC and ABF

Figure 8a–d shows the simulation of the residual SI power after only transmit and receive ABF, only baseband digital SIC, and aperture-level digital SIC. It can be seen that without a digital SIC and both transmit and receive ABF, all residual SI power is suppressed below the receiver channel noise, and both the baseband digital SIC and the aperture-level digital SIC can cancel out the SI terms generated by the transmitted signal. The main component of the total SI term remaining after the baseband digital SIC is the SI term generated by the transmit noise. The SI caused by the transmit noise that cannot be offset by the baseband digital SIC can be further offset by the introduction of the observation link; the receiver noise caused by the observation noise introduced by the observation link is basically the same; and the simulation results show that the EII obtained by the aperture-level digital SIC is 22.3 dB higher than that obtained by the baseband digital SIC. As can be seen from Figure 8e,f, the SI can be reduced below the noise of the receive channel when both the baseband digital SIC, the transmit and receive ABF are performed. With aperture-level digital SIC, and transmit and receive ABFs combined, the various SIs can also be reduced to the level of receive channel noise.

Figure 8 also shows the simulation analysis of the SI power of the digital SIC and the transmit and receive ABF. It can be seen that when the digital SIC is not performed and both the transmit and receive ABF are performed, the residual SI power is suppressed below the receiver channel noise, and the SI power generated by the transmit noise is reduced from about 30 dBm to about −170 dBm. Transmit and receive ABF on the basis of digital SIC can further reduce the residual SI power below the receiver channel noise.

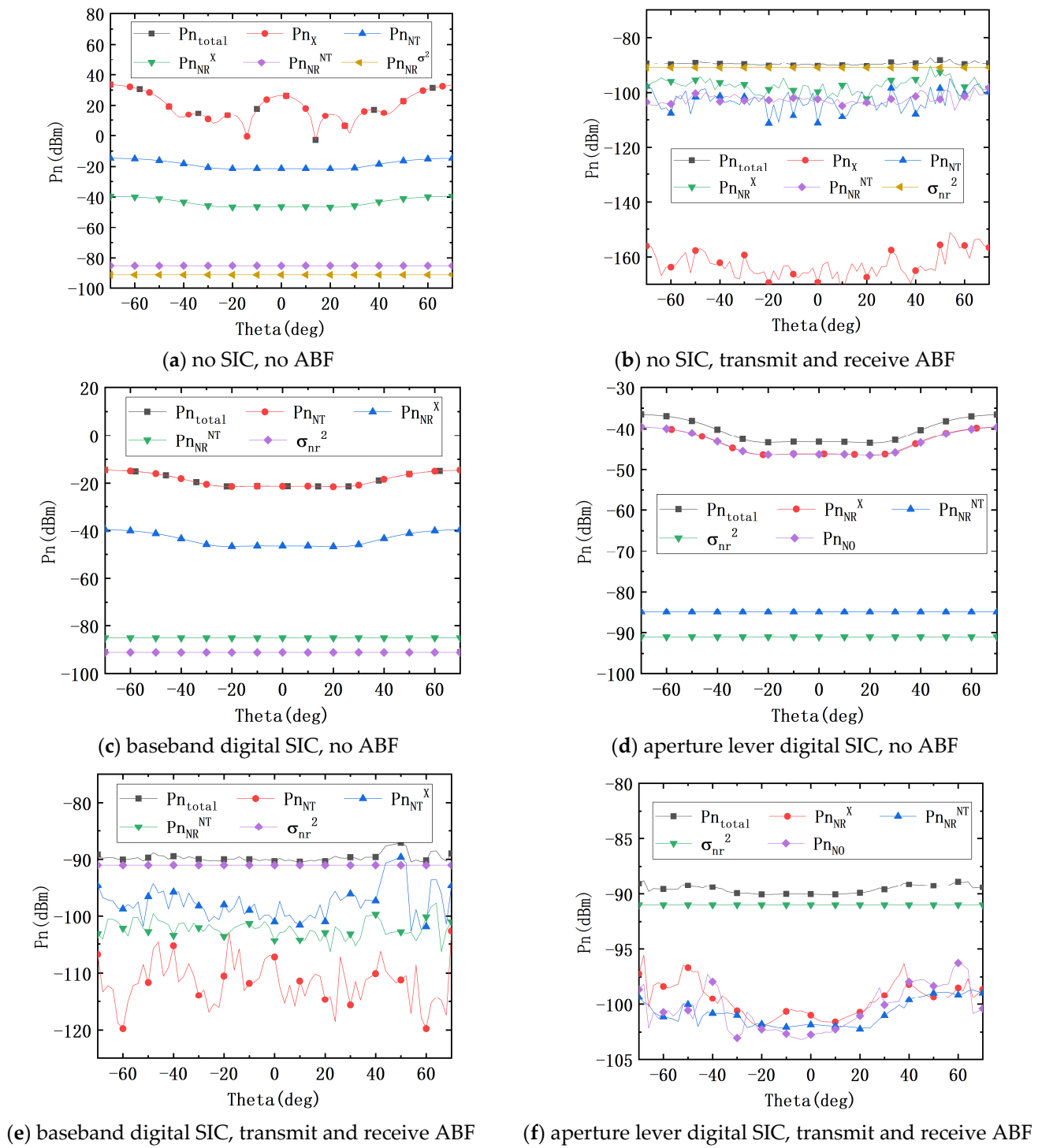


Figure 8. Residual SI analysis of SIC and transmit and receive ABFs.

3.2.2. Comparative Analysis of Transmit ABF and Receive ABF

Furthermore, the residual SI powers of transmit ABF, receive ABF, transmit and receive ABF are analyzed in the absence of SIC, baseband digital SIC, and aperture-level digital SIC, respectively.

Figure 9 and Table 3 show the residual SI without SIC and transmit and receive ABFs and the residual SI powers of the non-SIC and transmit and receive ABFs at a beam scanning angle of 0° , respectively.

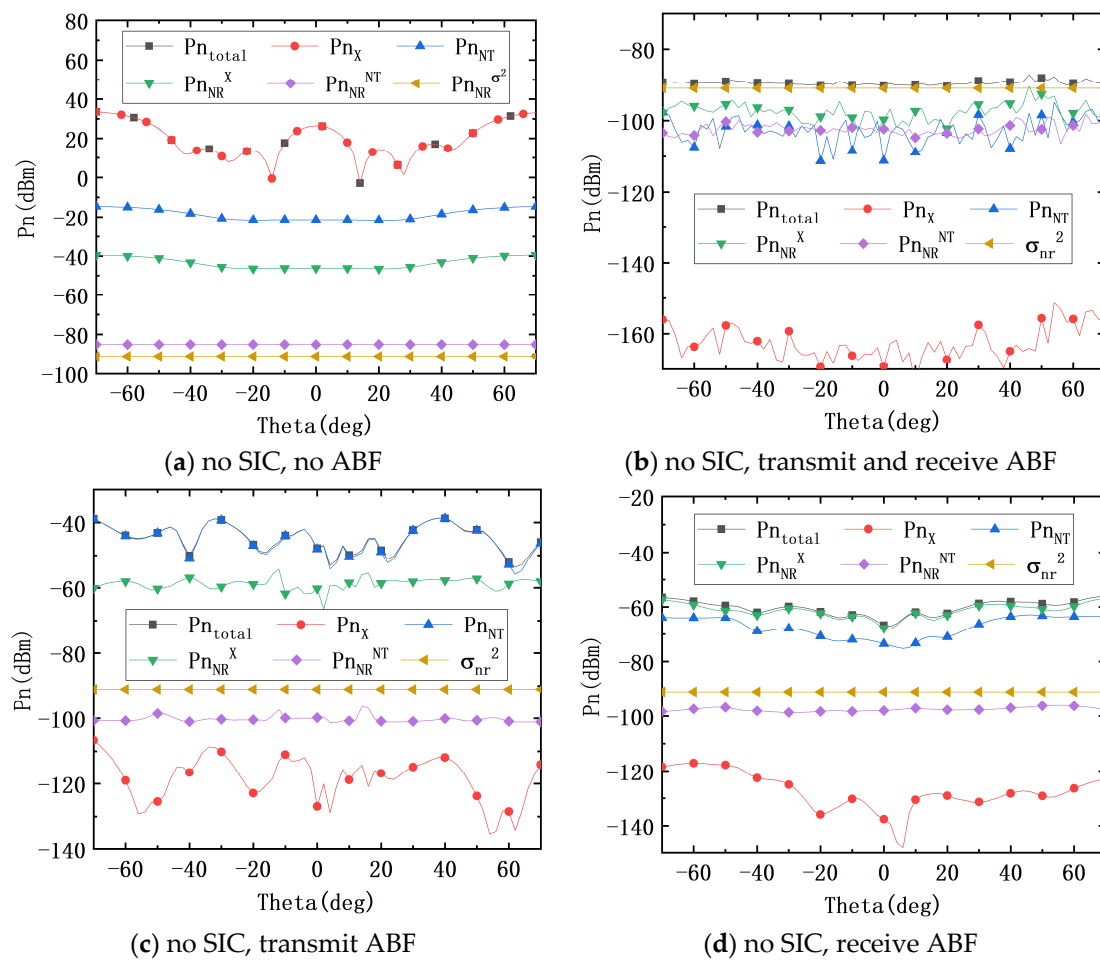


Figure 9. Residual SI analysis without SIC and transmit and receive ABF.

Table 3. Each residual SI power of ABF without SIC.

SI Item	No ABF	Transmit ABF	Receive ABF	Transmit and Receive ABF
P_X	26.4 dBm	−132.6 dBm	−149.2 dBm	−172.1 dBm
P_{NT}	−21.3 dBm	−47.7 dBm	−73.7 dBm	−112.4 dBm
P_{NR}^X	−45.6 dBm	−70.9 dBm	−66.7 dBm	−99.3 dBm
P_{NR}^{NT}	−84.3 dBm	−101.3 dBm	−99.6 dBm	−101.2 dBm
σ_{nr}^2	−91 dBm	−91 dBm	−91 dBm	−91 dBm
P_{n_total}	26.4 dBm	−47.7 dBm	−66.7 dBm	−90.0 dBm

As can be seen from Figure 9 and Table 3, in the absence of SIC, the transmit ABF and the receive ABF have a suppression effect on each of the total interference power, and both can suppress the interference generated by the transmitted signal and the receiver noise caused by the transmitted noise below the receiver channel noise. The suppression effect of transmit ABF and receive ABF on the receiver noise caused by the transmitted signal is basically the same. However, neither the transmit ABF nor the receive ABF can completely cancel out the SI generated by the transmitted signal, and the suppression effect of the transmit ABF on the SI generated by the transmitted signal and the SI generated by the transmitted noise is lower than that of the receive ABF. Therefore, the EII of receive ABF is 20.8 dB higher than that of transmit ABF.

Figure 10 shows the analysis and comparison of the residual SI power in the case of baseband digital SIC. As shown in Figure 10a, the baseband digital SIC can completely cancel out the SI power generated by the transmitted signal. As can be seen from Figure 10b, the transmission and receive ABF based on the baseband digital SIC can further reduce

the residual interference noise to the transmitter channel noise, and the cancellation of the interference noise is basically the same as that of the transmit and receive ABF without SIC. As can be seen from Figure 10c,d, both transmit ABF and receive ABF on the baseband digital SIC can suppress the receiver noise caused by the transmit noise to the receiver channel noise, but the SIC effect of the received ABF on the transmit noise is greater than that of the received ABF due to the transmit ABF. Table 4 shows the residual SI analysis of the baseband digital SIC, transmit and receive ABF, and the residual SI power of the non-SIC and transmit and receive ABF at a scan angle of 0° .

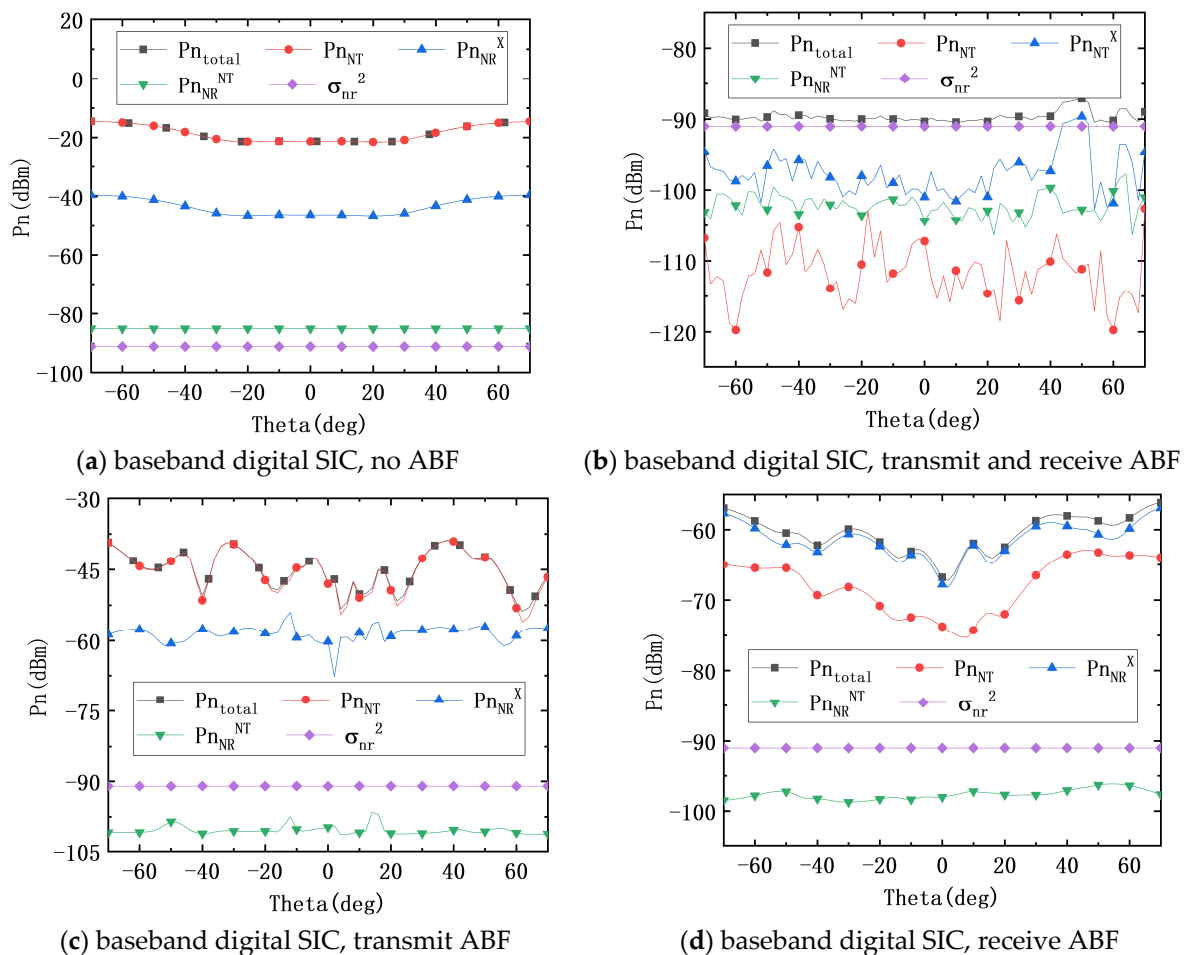


Figure 10. Residual SI analysis of baseband digital SIC and transmit and receive ABF.

Table 4. Each residual SI power of ABF at baseband digital SIC.

SI Item	No ABF	Transmit ABF	Receive ABF	Transmit and Receive ABF
P_X	0	0	0	0
P_{NT}	−21.3 dBm	−47.7 dBm	−73.7 dBm	−112.4 dBm
P_{NR}^x	−45.6 dBm	−70.9 dBm	−66.7 dBm	−99.3 dBm
P_{NR}^{nt}	−84.3 dBm	−101.3 dBm	−99.6 dBm	−101.2 dBm
σ_{nr}^2	−91 dBm	−91 dBm	−91 dBm	−91 dBm
P_{n_total}	−21.3 dBm	−47.8 dBm	−66.7 dBm	−90.1 dBm

Figure 11 shows the analysis and comparison of the residual SI power in the case of aperture-level digital SIC. As can be seen from Figure 11a,b, the SI generated by the transmitted signal and the transmitted noise can be completely canceled out in the case of aperture-level digital SIC and no ABF, at the cost of introducing the noise of the observation channel, but the noise of the observation channel is basically the same as the noise of the

receiver caused by the transmitted signal and is 26 dBm smaller than the SI caused by the transmitted noise. The transmit and receive ABF based on the aperture-level digital SIC can suppress the residual SI under the noise of the receive channel, and the noise power is basically the same. Figure 11c,d shows that on the basis of the aperture-level digital SIC, the residual SI suppression effect of transmit ABF and receive ABF is basically the same; both can reduce the residual SI, and both can only suppress the SI caused by the transmit noise below the receive channel noise. However, as can be seen from Figure 11, the suppression effect of transmit ABF and receive ABF on the receiver noise caused by the transmitted signal is better than that of the observed channel noise. Table 5 shows the residual SI analysis of the baseband digital SIC and transmit and receive ABFs and the residual SI powers of the non-SIC and transmit and receive ABFs at a scan angle of less than 0° .

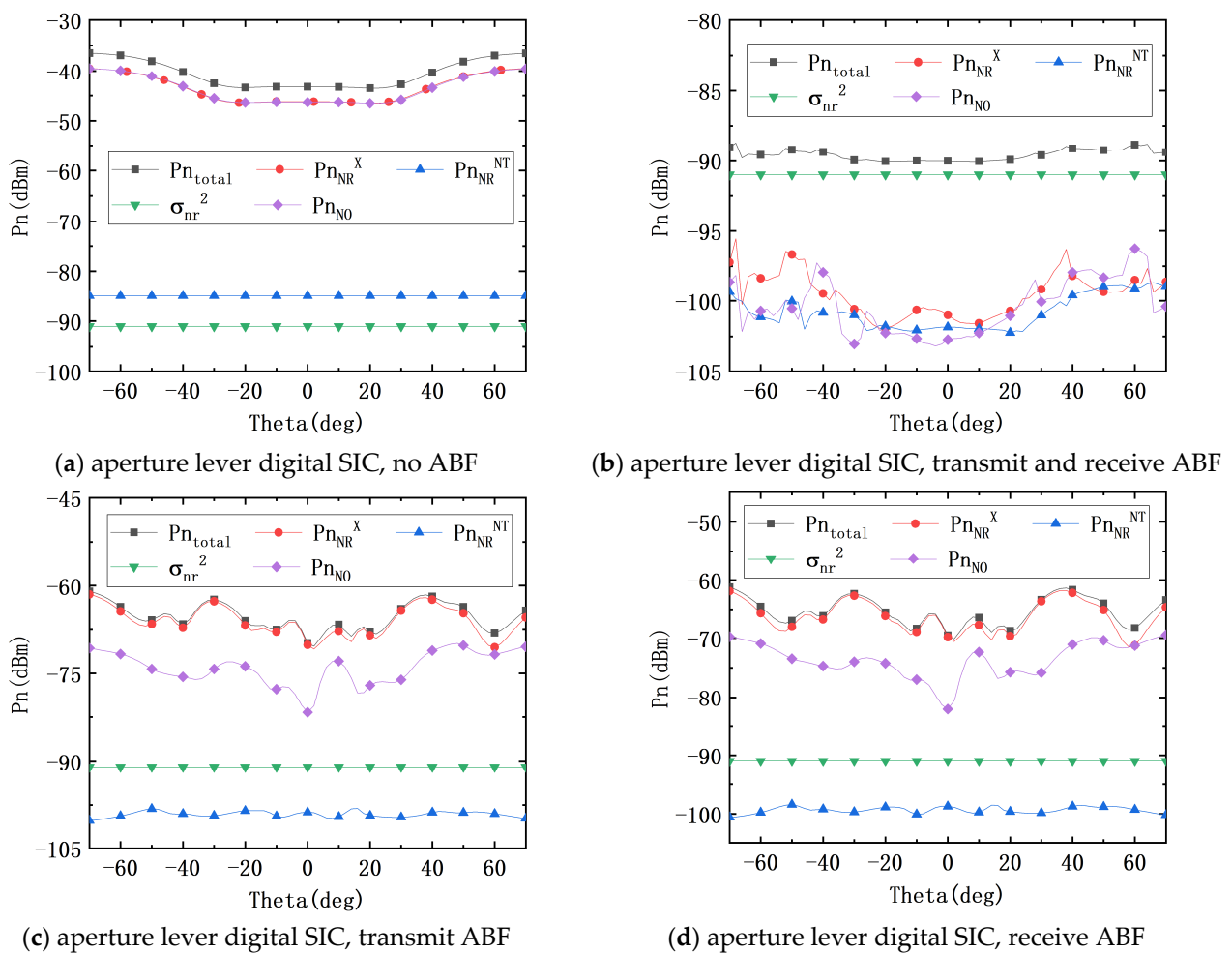


Figure 11. Residual SI analysis of aperture lever digital SIC and transmit and receive ABF.

Table 5. Each residual SI power of ABF at aperture-level digital SIC.

SI Item	No ABF	Transmit ABF	Receive ABF	Transmit and Receive ABF
P_X	0	0	0	0
P_{NT}	0	0	0	0
P_{NR}^X	−45.6 dBm	−69.1 dBm	−69.3 dBm	−101.9 dBm
P_{NR}^{NT}	−4.3 dBm	−100.2 dBm	−100.8 dBm	−101.5 dBm
P_{NO}	−45.6 dBm	−79.3 dBm	−79.3 dBm	−101.4 dBm
σ_{nr}^2	−91 dBm	−91 dBm	−91 dBm	−91 dBm
P_{n_total}	−43.2 dBm	−69.5 dBm	−69.8 dBm	−90.2 dBm

From the above analysis, it can be seen that the SIC effect of receive ABF on the basis of no SIC and baseband digital SIC is better than that of transmit ABF because the SI suppression effect of receive ABF on the transmitted noise is better than that of transmit ABF. The aperture-level digital SIC completely cancels out the SI generated by the transmitted signal and the transmitted noise, so the effect of transmit ABF and receive ABF on its basis is the same. The above conclusion applies to communication and radar systems under simultaneous transmission and reception systems.

4. Conclusions

In this paper, the STAR digital SIC cancellation and beamforming airspace cancellation models are analyzed. The residual noise power and isolation performance indexes of the loaded baseband digital SIC, aperture-level digital SIC, and beamforming STAR arrays are derived. Theoretical analysis and experimental results show that the EII of transmit ABF in the baseband digital SIC is 20 dB higher than that of receive ABF, and the EII ratio of transmit ABF in the aperture-level digital SIC is consistent with that of receive ABF. On the baseband digital SIC, both the transmit ABF and the receive ABF can suppress the receiver noise caused by the transmit noise to the receiver channel noise, but the SI suppression effect of the received ABF on the transmit noise is better than that of the transmit ABF, so the total residual SI power of the transmit ABF is greater than that of the received ABF. On the basis of the aperture-level digital SIC, only transmit ABF and receive ABF have basically the same effect on the residual SI, and both can reduce the residual SI. This article discusses the basic STAR array model, which involves the mathematical model derivation and simulation verification of digital SIC. The work presented in this article can provide fundamental theoretical support for specific SIC technology research.

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