Recent Breakthroughs on Angle-of-Arrival Estimation for Millimeter-Wave High-Speed Railway Communication

Kai Wu, Wei Ni, Tao Su, Ren Ping Liu and Y. Jay Guo

Abstract—**With significantly improved efficiency, large-scale hybrid antenna arrays with tens to hundreds of antennas have great potential to support millimetre-wave (mmWave) communication for high-speed railway (HSR) applications. The significant beamforming gains rely on fast and accurate estimation of the angle-of-arrival (AoA), which however can be impeded by the high train speed, cost/energy oriented design of arrays, and the severe attenuation of mmWave signals. This article reviews these challenges, and discusses the limitations of existing AoA estimation techniques under hybrid antenna array settings. The article further reveals a few recent theoretical breakthroughs which can potentially enable fast and reliable estimation, even based on severely attenuated signals. Under a speed setting of 500 km/h, a performance study is carried out to confirm the significant improvements of estimation accuracy and subsequent beamforming gains as the results of the breakthroughs.**

Index Terms—**millimeter wave (mmWave); high-speed railway (HSR); phased array; hybrid antenna array; lens antenna array.**

I. Hybrid Antenna Array for High-Speed Railway Communication

Being an efficient and sustainable land transport method, future high-speed railway (HSR) is envisaged to be safer, greener and more convenient [1], [2]. Given increased passenger capacity of high-speed trains (HSTs), there are expected to be a substantially increased number of wireless connections between passengers and the Internet. As illustrated in Fig. 1, a practical scenario is to have a train-top antenna array to act as the proxy to relay in-cabin (WiFi, cellular or Ethernet) traffic to track-side base stations (BSs) or communication satellites. Given the scarcity of frequencies and the demand for high data rates of tens of gigabits per second (Gbps) [1], [3], high carrier frequencies with broad bandwidths, such as millimeter-wave (mmWave) or even terahertz (THz), are likely to be used. The mmWave frequency range of $24.25 - 52.6$ GHz has been specified in 5G new radio, and considered in HST scenario [4]. Feasibility studies, including extensive measurement campaigns, have been conducted to confirm the validity of the consideration. For example, a 30 GHz large-scale hybrid array has been tested over an HST link between an onboard relay and track-side infrastructure [4]. A significant improvement of spectral efficiency compared with legacy LTE-configured HST has been demonstrated at the train speed of 500 km/h [4, Fig. 5]. THz antenna arrays still have issues in compact and efficient design [1], but have started to show a good prospect. For example, a recent work [5] has reported a 400-GHz THz antenna array with a measured gain of 33.66 dBi.

A. Large-scale Hybrid Antenna Array

Large-scale antenna arrays have a range of advantages, e.g., in the mmWave frequency band. The arrays are able to achieve tunable/steerable narrow beams with high gains to combat the severe attenuation the mmWave bands. The narrow beams can also help suppress interference and improve the effective signal-to-interference-plus-noise ratio of intended signals. For example, the beamwidth of a $1,000$-element uniform linear array is about 0.0126 rad, which is only two percent of the beamwidth of a 20-element counterpart. The short wavelength of the mmWave frequency makes the integration of hundreds to thousands of antenna elements per array possible [6]. A linear aperture size of 150 cm can accommodate up to 300 elements with antenna spacing of half wavelength at 30 GHz, while it can only accommodate 20 elements at 2 GHz.

A hybrid antenna array becomes a preferable and cost-effective design of large-scale antenna arrays, where a large number of antennas are grouped and connected into a much smaller number of analog subarrays. Each antenna has an individual configurable phase shifter. Each subarray is connected to a single radio frequency (RF) chain. This is because the physical sizes of RF chains, consisting of analog-to-digital and digital-to-analog converters, power amplifiers, and filters, do not shrink in the mmWave frequency band, as compared to the lower frequencies. Hardware impairments, like different delays in RF components, can be calibrated and suppressed before baseband digital signal processing.

A one-dimensional linear large-scale hybrid array is shown in Fig. 2. The subarrays are typically arranged in a localized fashion to facilitate wiring and schematic design [7]. The subarrays can consist of discrete antenna elements. The resulting array is referred to as Discrete Antenna Array (DAA), which is typically a one-dimensional uniform linear array. In a recent 3GPP HST evaluation [4], a 30-GHz large-scale hybrid array with 256 antennas was installed at an onboard relay. The array is rectangular with four 8×8 analog subarrays and four RF chains. The antenna spacing is half of a wavelength. With considerations on energy and cost efficiency, and integration level, a subarray can be replaced with a lens antenna or a Butler matrix, as also shown in Fig. 2.

In the case of lens antenna array, each subarray is a lens antenna array [6], [8]. The lens can focus the microwave signals onto its parabola focal surface. By meticulously placing the antennas on the focal surface of the lens, a complete set of discrete Fourier transform (DFT) beams can be activated with sinc-shape beam patterns and pointing directions evenly spaced within $[0, 2\pi)$. Each antenna, referred to as a *beam port*, can be energized to activate a DFT beam. A switch can be used to select a beam port, and connect the selected beam port to the RF chain hardwired to the switch [6].

In the case of Butler matrix array, each subarray is a Butler matrix which is a passive analog beamforming circuit. The Butler matrix also generates DFT beams. Each beam port can activate an individual DFT beam, like the lens antenna. Also like the lens antenna array, a switch can be used to select and connect a beam port to an RF chain in the Butler matrix arrays. The beam pattern of a DFT beam is a sinc function within $[0, 2\pi)$, as shown on the left-hand side of Fig. 3. The beam width of the mainlobe depends on the number of antennas. The mainlobe can be shifted (or rotated) by changing the phases of the antennas [8, eq. 7].

The Lens antenna arrays and Butler matrix arrays can be much more energy-efficient than the phase shifter based DAAs due to their high integration level. The lens and Bulter matrix are passive beamformers, while the phase shifters consume non-negligible powers. The typical power consumption of a 4-bit mmWave phase shifter is 30 mW [6]. To produce a 16-dimensional DFT beam, a total of 16 phase shifters are required, consuming $30 \times 16 = 480$ mW power. In contrast, the power consumption of an equivalent lens antenna array is only 4 mW [6].

The one-dimensional Butler matrices and lens antennas can both be readily extended to two-dimensional uniform planar arrays, due to the fact that the DFT beams can be decoupled losslessly between the azimuth and elevation [9]. The DAAs can also be readily extended to two-dimensional uniform planar arrays if DFT beams are adopted. There are also other forms of hybrid antenna arrays, such as fully-connected array and uniform circular array. Overall, they are less tractable due to too many cross-points (in fully connected hybrid arrays) or weak directivity (in uniform circular arrays). Therefore, they are far less popular in practice.

B. Fast Angular Estimation and Tracking of HST

The train-top array and its counterparts at the track-side BSs or satellites are expected to be large-scale to produce narrow beams with high gains, thereby combating severe attenuation at mmWave frequencies. The arrays are also anticipated to be hybrid with localized architectures in consideration of cost-efficiency and size. Omni-directional transmission could be possible at lower frequencies, but the limited bandwidths available at those frequencies are not wide enough to support Gbps [1]. To this end, accurate estimation and reliable tracking of the angle-of-arrival (AoA) from an HST to the track-side BSs or satellites, or the other way around, is critical to the implementation of the mmWave HSR communication systems.

The AoA estimation is indispensable for efficient utilization of mmWave phased arrays in 5G. It allows for accurately configuring the arrays to quickly capture the impinging signal, form narrow and strong beams, and achieve high signal-to-noise (SNR) and throughput. The fast and accurate AoA estimation can also avoid the round-trip delay of the typical channel estimation and feedback, hence speeding up beamforming and guaranteeing seamless and reliable connectivity.

Conventional channel estimation techniques involving channel sounding, estimation, and feedback would become inadequate. This is because the number of RF chains is much smaller than that of antennas (beams) in mmWave frequency bands given the increasingly compact design of antennas. In contrast, conventional channel estimation approaches were typically designed for digital arrays with the equal numbers of antennas and RF chains in lower frequencies. Important channel information which was accessible to digital arrays, such as the phase difference between antennas, is not readily accessible in the mmWave hybrid antenna arrays. The estimation and feedback could become excessively frequent and likely to be outdated in the HSR application where the trains can travel at very high speeds of up to 500 km/h. It is important that a train-top mmWave antenna array and its counterpart at the track-side BSs (or satellites) can estimate the AoAs passively and instantly based on the impinging signals from each other, steer and lock their beams, and keep tracking the changes of AoAs to adapt the beams.

II. Challenge and State of the Art of AoA Estimation for Large-Scale Hybrid Arrays

To estimate the AoA in the large-scale hybrid antenna arrays is non-trivial with several key challenges to be properly addressed. None of existing techniques are able to address the challenges holistically. In this section, we start with three key challenges, followed by a review of the state of the art.

A. Estimation Ambiguity

There is a long-standing estimation ambiguity originating from the architecture of localized hybrid antenna arrays where the received signals at the different antenna elements of a subarray are mixed (or added up) before being sent into an RF chain. The phase difference between adjacent antenna elements, which gives the estimate of the AoA, becomes obscure. Only the phase difference between adjacent subarrays is available, which is a multiple of the inter-element phase difference and needs to be divided by the number of antenna elements in each subarray. Unfortunately, a division of an angle (or phase) gives ambiguous results due to the 2π periodicity of angles (or phases).

B. Channel Property

In most cases, HSTs have unobstructed line-of-sight (LoS) to the track-side BSs. When penetrating buildings and propagating through foliage, mmWave signals attenuate significantly. For these reasons, the mmWave HSR channels are typically dominated by strong LoS paths [1], [3], [10], and can be modeled as Rician channels [11]. Ray-tracing techniques have been employed to simulate the Rician factor – the ratio between the power in the LoS path and the power in the scattered paths – in typical outdoor scenarios. As reported in [10, Tab. II], the power in the LoS path is at least 11 dB stronger than the total power in the other paths in the outdoor 30 GHz channels.

The HSR channels can also exhibit strong temporal variations, due to the speed of up to 500 km/h of the HSTs [12]. The conventional omnidirectional broadcast is not suitable for the mmWave frequencies, because of severe attenuations at the frequencies. The received SNR can be very low. For example, the received SNR is around -20 dB at each antenna, when the carry frequency is 100 GHz, the bandwidth is 1 GHz, the transmit power is 20 dBm, the transmitter-receiver distance is 100 m, and both the transmit and receive antennas have unit gains [1]. It is necessary to exploit the strong directivity and gains of efficient mmWave antennas to track and uninterruptedly serve the HSTs.

C. State of The Art

The two best-known AoA estimation techniques are multiple signal classification (MUSIC) [13] and estimation of signal parameters via rotational invariance techniques (ESPRIT) [13]. Developed originally for full-digital arrays [13], these techniques exploit the orthogonality of the signal and noise subspaces to estimate the signal subspace which is the span of the array response vectors in the directions of the AoAs. MUSIC takes the autocorrelation of received array signals, and estimates the signal subspace as the eigenvectors associated with the large, meaningful eigenvalues of the autocorrelation matrix. ESPRIT divides an array into two subarrays, calculates the transformation matrix between the signal subspaces of the two subarrays, and estimates the AoA from the eigenvalues of the matrix. Computationally expensive singular value decomposition (SVD) is required in both techniques, and could hinder the scalability of the techniques. MUSIC and ESPRIT cannot be directly applied to hybrid antenna arrays, due to the RF combining at analog subarrays and the resultant obscurity of the phase offset information on individual antennas.

Recently, cross-correlation based AoA estimation methods [9], [14], [15] have been developed for hybrid antenna arrays, which extract the AoA information from the cross-correlations of either subarray outputs [9] or the inverse DFT of selected subarray outputs [14], [15]. The methods [9], [14], [15] have low computational complexities, since only a small number of complex multiplications and low-dimensional DFTs are involved. Given these advantages, the cross-correlation based AoA estimation techniques can be potentially suitable for mmWave high-speed railway communications. However, the existing methods [9], [14], [15] suffer from the estimation ambiguities which degrade estimation accuracy, as described in Section II-A.

III. Breakthroughs enabling Fast Tracking of High-Speed Trains

Despite the estimation ambiguity and long angular search delay, cross-correlation based approaches [9], [14], [15] are still the most appropriate for mmWave HSR communications, due to their strong tolerance to the severe Doppler effect and compatibility with hybrid antenna array structure. New ground-breaking findings are uncovered to eliminate the ambiguity and significantly expedite the estimation and tracking of the AoA within sub-milliseconds.

A. Ground-breaking Discoveries

One of the significant findings is that, when the analog subarrays point at the angles evenly spaced within $[0, 2\pi)$, there is an underlying deterministic pattern in the cross-correlations of the received signals between adjacent subarrays at any time [15, Theorem 1]. The pattern can be revealed as follows:

The cross-correlations of received signals between adjacent analog subarrays have consistent signs. The only exception is the strongest cross-correlation which takes the opposite sign from the rest.

The reason behind this finding is that the sign of a cross-correlation depends on the product of two sine functions which are the denominators of the standard sinc-function beam patterns of the two consecutive subarrays. It has been proved in [15] that the two sine functions take opposite signs, only when the mainlobes of the two consecutive subarrays are on the different sides of the impinging signal. Moreover, the mainlobes of this pair of subarrays are closer to the impinging signal than the mainlobes of the remaining pairs of consecutive subarrays. Therefore, the cross-correlation of the pair is stronger than those of the rest.

This finding is important, as it enables us to quickly and reliably identify the pair of adjacent subarrays providing the cross-correlation with the opposite sign. We can correct the sign, and then coherently combine all the cross-correlations to enhance the SNR for the estimation of the phase difference between adjacent analog subarrays, and estimate the phase difference unambiguously. The finding is also very insightful, as the strongest cross-correlation is the least susceptible to receiver noises and most unlikely to be mistaken.

The finding can be extended to multiple time slots (or training symbols), where angularly evenly spaced DFT beams are produced at every symbol. Only the pairs of consecutive subarrays with their mainlobes on the different sides of the impinging signal have cross-correlations with the opposite sign to the rest of the pairs at each symbol. The use of multiple symbols can collectively narrow down the angular region of the impinging signal.

In the presence of non-negligible noise, estimation inaccuracies can occur. Since the strongest cross-correlation is expected to take the opposite sign at every symbol, they are the least likely to be corrupted by noise. This provides the most reliable and noise-resisting estimation by identifying the pairs of consecutive subarrays which each have the strongest cross-correlation at one of the training symbols and all have an overlapping angular region between their mainlobes. This gives the best possible estimation accuracy of the phase difference between consecutive subarrays.

Another breakthrough is that, when the analog subarrays point at angles evenly spaced within $[0, 2\pi)$, the received signals of the subarrays can be augmented to achieve the unambiguous estimation of the AoA [14], [15, Theorem 2]:

Provided that the phase offsets between adjacent analog subarrays are perfectly canceled, the received signals of the angularly evenly spaced subarrays form a Fourier series. The phase of the Fourier coefficients provides an unambiguous estimate of the AoA.

The reason behind this finding is that the angularly evenly spaced subarrays receive the same impinging signal using different beam lobes. Since all the subarrays have the same sinc-function beam pattern, the received signals of the subarrays (after the phase differences between the subarrays are removed) can be interpreted as evenly spaced samples of the sinc-function beam pattern, as shown in Fig. 3. This gives a complete Fourier (or DFT) series with an additional phase which can uniquely determine the AoA of the impinging signal.

By following the ground-breaking discoveries, the AoA can be quickly and reliably estimated at a large-scale hybrid antenna array, even in low SNR regimes.

B. Algorithm Implementation

The two findings can be translated to simple executable operations for the unambiguous estimation of the AoA. The following three steps can be formed:

1) Steer the analog subarrays towards angles evenly spaced angles between $[0, 2\pi)$ during a training symbol (by configuring the phase shifters of the DAAs or selecting the DFT beams of the lens and Butler matrix arrays). If multiple symbols are used, rotate the beams altogether in steps to increase the angular resolution of evenly spaced pointing angles;
2) Take cross-correlations between the received signals of adjacent subarrays,
   a) In the case of a single symbol, identify the strongest cross-correlation and invert its sign before additively combining all the cross-correlations;
   b) In the case of multiple symbols, utilize the recognizable two-dimensional pattern of the signs of the cross-correlations over the symbols to identify the two cross-correlations with the opposite sign, and invert their signs before additively combining all the cross-correlations;

   and then estimate the phase of the combined cross-correlations as the phase difference between subarrays;
3) Augment the received signal at every subarray by canceling the inter-subarray phase difference, take the inverse DFT of the augmented signals, and finally estimate the AoA from the phase difference between consecutive Fourier coefficients.

The system framework of the new unambiguous estimation of the AoA is provided in Fig. 4, where Steps 1), 2) and 3) are highlighted in different frames. A single training symbol is taken as an example.

IV. Performance Study

Numerical studies are provided to evaluate the application of hybrid arrays in mmWave HSR communications. A typical 30-GHz railway system with 500 MHz bandwidth is considered [10]. A localized hybrid array with 4 subarrays is installed on the roof of the train, where the subarrays can be a phase shifter based DAA, a lens antenna array, or a Butler matrix array. The antennas in the subarrays are omnidirectional with unit gain.

The BS transmits signals to the HST with 30 dBm transmitting power and 25 dBi antenna gain, while the HST travels away from the BS at 500 km/h and the distance from the HST and BS grows from 10 m to 1 km during this performance study. Based on the RF thermal noise approximation [3], the received SNR of the system at the antenna elements decreases from 20 dB to -20 dB, as the transmitter-receiver distance increases from 10 m to 1 km. We assume a Rician channel with a direct LoS path and two indirect paths. We set the Rician factor to grow with the transmitter-receiver distance. The Rician factor is 10 dB when the distance is 10 m, and 30 dB when the distance is 1 km, as suggested by the measurement results [10, Tab. II]. The AoA of the direct LoS path is uniformly distributed in $[0, 2\pi)$ rad. The Doppler frequency follows the Gaussian distribution with the mean of 10 kHz and the standard deviation of 5 kHz.

Fig. 5 plots the mean squared error (MSE) of AoA estimates as the received SNR at the hybrid antenna arrays increases, where different number of antennas per subarray are taken. The figure provides the average result of $20,000$ independent trials under each SNR value. For each trial, the AoAs of a direct LoS path and two indirect paths, and the Doppler frequency of the direct path are randomly and independently generated. The algorithm described in Section III-B is performed to estimate the AoA of the direct path. We see that the new AoA estimation approach can achieve very low estimation errors, even in low SNR regions. Specifically, the MSE can be as low as 1.6×10^{-4} at -20 dB SNR, thanks to the new findings unveiled in Section III. We also see that the MSE decreases markedly, as the number of antennas per subarray increases from 8 to 40. The improvement can be as large as 75.46%. Moreover, as observed in Fig. 4, the AoA estimation accuracy can be improved by increasing the number of antennas in each subarray. Since the number of subarrays is not increased, the computational complexity does not grow with the increasing number of antennas per subarray and the improving estimation accuracy. In other words, the AoA estimation accuracy can be substantially improved by cost-effectively integrating more antennas for each subarray.

Fig. 5 also validates the efficiency and accuracy of the new AoA estimation approach, as compared to the state-of-the-art approach specifically designed for localized hybrid arrays [9]. We see that the new approach can substantially outperform the state of the art. In low SNR regions, the new technique can reduce the MSE of the AoA estimation by as much as 95.99% with 80% less number of symbols, as compared to the state of the art. We note that the results apply to all of the DAA, lens antenna array, and Butler matrix array, or any localized hybrid array with subarrays capable of producing DFT beams. Despite their different structures and integration levels, the DAA, lens antenna, and Butler matrix can all produce DFT beams.

Fig. 6 provides the complementary cumulative distribution function (CCDF) of the subarray beamforming gain that is calculated based on the AoA estimates at -20 dB SNR from Fig. 5. The subarray beaforming gain is obtained by steering all the subarrays to the closet possible angle around the estimated AoA. Despite the phase shifter based DAA, lens and Butler matrix arrays can all achieve the same AoA estimation accuracy, as discussed in Fig. 4. The DAA can accurately form a beam to the estimated AoA; while the lens and Butler matrix can only select the angularly closest DFT beam from their discrete sets of DFT beams, leading to gain losses. Since the lens and Butler matrix arrays are expected to give exactly the same results, they are both represented by the same curve in Fig. 5 to keep the figure clear.

We also see in Fig. 6 that large beamforming gains can be achieved, given the fine AoA estimation accuracy. The beamforming gains based on phase shifters can be greater than 86.58% of the maximum-achievable gain, i.e., the number of antennas, in no less than 90% of all cases. We also see that the lens or Butler matrix based beamforming gains can be smaller than the gain based on phase shifters. As mentioned, this is caused by the fixed DFT beamforming of the lens antennas and Butler matrices, which is the price paid for increased system integration level and energy efficiency.

V. Conclusion

This article reviews existing AoA estimation techniques, and discusses their limitations under mmWave hybrid antenna array and high-speed settings. A few recent theoretical breakthroughs are presented, where the deterministic properties of the complex beamforming gains of hybrid antenna arrays are unveiled. It is demonstrated that the breakthroughs can potentially enable fast and reliable estimation of the AoA, even based on severely attenuated signals in high-speed scenarios. Under a speed setting of 500 km, a performance study shows the significant improvements of estimation accuracy and subsequent beamforming gains as the results of the breakthroughs, even at a low SNR of -20 dB.

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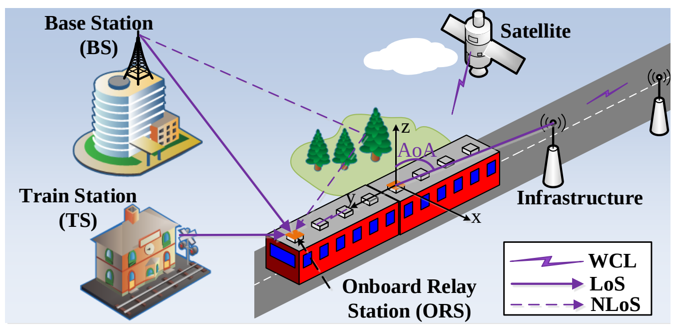

Fig. 1. Schematic diagram of the "smart" railway communication system with the interconnections between the HST and BS, TS, infrastructures, as well as satellite. WCL refers to wireless communication link.

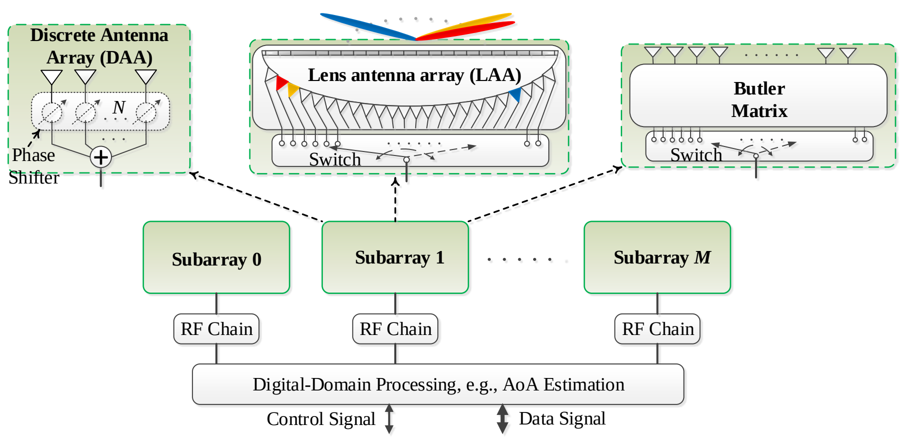

Fig. 2. Schematic diagram of a one-dimensional localized hybrid array, where the subarrays can be implemented by either generic discrete antenna elements, or highly integrated antennas such as lens and Butler matrix.

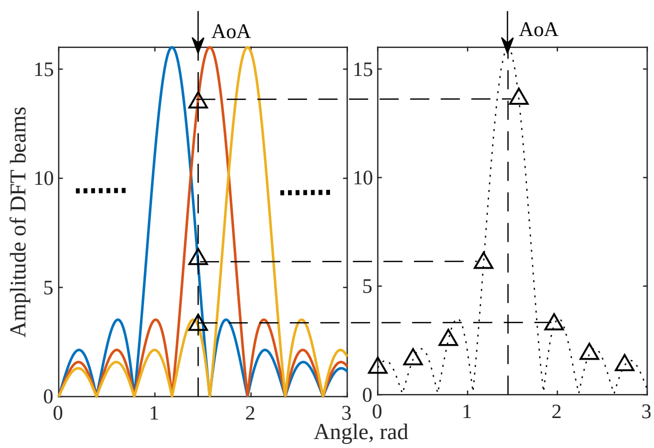

Fig. 3. Illustration of the amplitudes of consecutive DFT beams and the responses of the DFT beams at the target AoA.

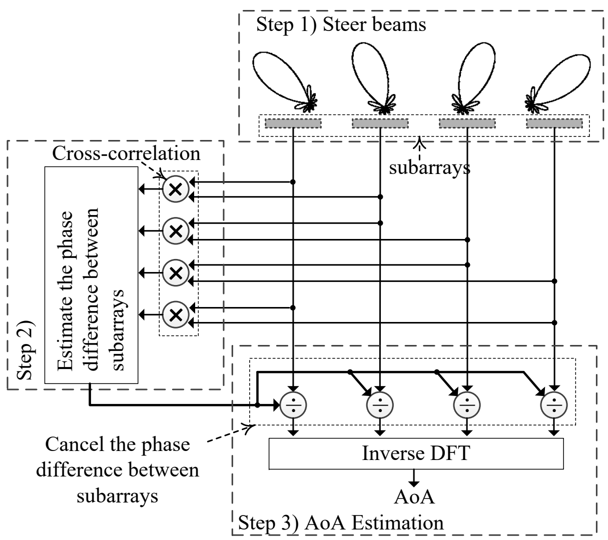

Fig. 4. System diagram of the new unambiguous AoA estimation algorithm developed based on the two new discoveries described in Section III-A.

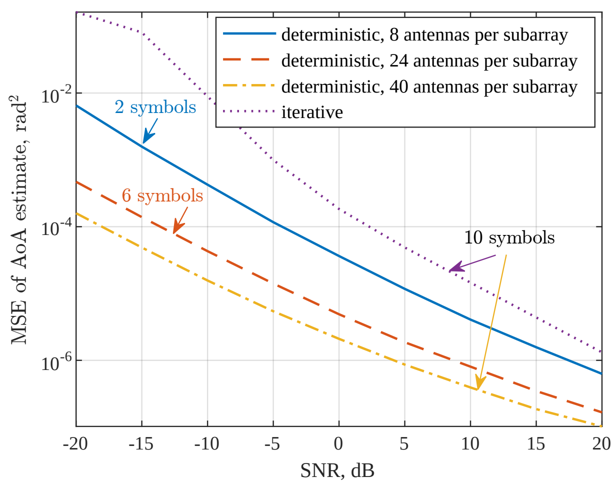

Fig. 5. MSE of AoA estimation vs the received SNR at antennas, where the new AoA estimation approach in Section III; referred to as "deterministic", is compared with the state-of-the-art approach, referred to as "iterative" [9].

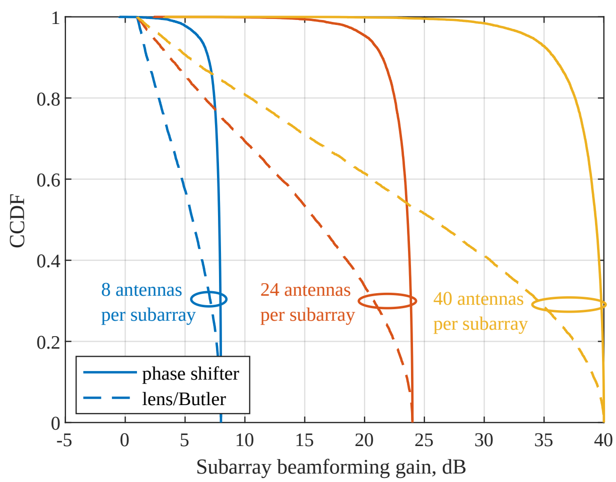

Fig. 6. CCDF of subarray gain based on the AoA estimates in Fig. 5.