Adaptive AoA Estimation and Beamforming with Hybrid Antenna Arrays

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Abstract—**A new type of hybrid antenna array consisting of analogue subarrays followed by a digital beamformer is proposed for practical implementation of long range high data rate millimetre wave communications systems. An adaptive algorithm, referred to as the differential beam search (DBS), is proposed for the angle of arrival (AoA) estimation to control the phase shifters in the analogue subarrays and to perform digital beamforming. This algorithm does not need the knowledge of a reference signal and effectively solves the phase ambiguity problem in AoA estimation inherent to the practical subarray configuration. The performance of the proposed DBS algorithms is demonstrated by simulations.**

Keywords— **Adaptive antenna array, subarray, angle of arrival estimation, digital beamforming, mm-wave communications.**

I. Introduction

With the growing demand for long range and high data rate wireless communications and the advance in digital signal processing techniques, adaptive antenna arrays have found a wide rage of applications and become an essential part of the wireless communications systems [1-3]. The use of adaptive antenna arrays for millimetre wave (mm-wave) mobile and ad hoc communication networks [4,5] is particularly critical due to the limited output power of the monolithic microwave integrated circuits (MMIC). Combing multiple antennas, each of which has its own power amplifier, to form an antenna array not only increases the transmit power but also enables the smart antenna technology to be applied to optimize the system performance.

Since the antenna elements must be spaced closely together to prevent grating lobes, the analogue components, such as the low noise amplifier (or power amplifier) and the down (or up) converter associated with each antenna element, must be tightly packed behind the antenna elements. At operating mm-wave frequencies of 55 and 95 GHz, the required element spacing is only 2.9 and 1.7 mm respectively. With the current MMIC technology, the practical implementation of such a digital antenna array remains as an engineering challenge due to the space constraint [6,7]. Furthermore, to perform digital beamforming with large bandwidth, each signal from/to an antenna element should be divided into a number of narrowband signals and processed digitally, which also adds to the cost of digital signal processing significantly. Therefore, a full digital implementation of wideband antenna array at mm-wave frequencies is simply unrealistic for large antenna arrays [8].

To overcome the difficulty, one can resort to subarray techniques, which divide the antenna elements in an array into groups [9]. In this paper, a new type of hybrid adaptive antenna array employing subarrays is proposed [10]. It consists of a number of analogue subarrays followed by a digital beamformer. The analogue subarray consists of a number of antennas and phase shifters fed by a corporate network. It helps reduce the cost of the radio frequency (RF) devices and the complexity of the digital beamformer. The digital beamformer produces the angle of arrival (AoA) information to control the values of the phase shifters in the analogue subarrays. The adaptive AoA estimation and beamforming algorithm, termed the differential beam search (DBS), is proposed for the hybrid antenna array with the typical subarray configuration in which the analogue subarrays are placed side-by-side for implementation practicability. The algorithm makes use of the phase difference between the adjacent received subarray outputs to estimate the AoA information. This blind nature of the algorithm removes the necessity of a known reference signal or signal synchronization at low signal-to-noise ratios (SNR) during the initial beam acquisition, which is required for conventional adaptive beamforming techniques such as the least mean squares (LMS) and iterative beam steering (IBS) algorithms [1,2]. The DBS algorithm also incorporates an effective beam search strategy to solve the phase ambiguity problem in AoA estimation which is inherent to the practical side-by-side subarray configuration.

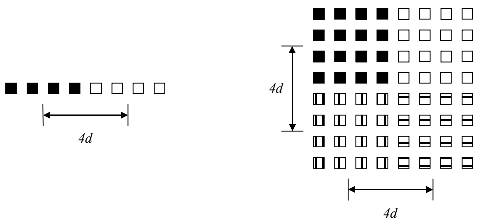
The rest of the paper is organized as follows. In Section II, the proposed hybrid antenna array composed of side-by-side analogue subarrays is described, and the received signal models for the subarray and hybrid antenna array output signals are given. Section III presents the detailed blind adaptive algorithm for AoA estimation and beamforming. Section IV provides the simulation results to show the performance of the proposed algorithm. Finally, conclusions are drawn in Section V.

II. Hybrid Array and Signal Models

A. Hybrid Array of Subarrays

A subarray is a subset of elements in an antenna array. In an analogue subarray, each element is connected to an analogue phase shifter. The received signals from individual elements after phase shifting are combined to produce the output signal of the analogue subarray. The output signal is then converted to digital domain via a down-converter and an analogue-to-digital converter (A/D). The proposed hybrid antenna array can be constructed by two or more such subarrays which are practically placed side-by-side with each other. Examples of the hybrid antenna arrays are shown in Fig. 1. Defining the distance between corresponding elements in adjacent subarrays as subarray spacing, it is seen that the subarray spacing is always larger than the element spacing which is the distance between adjacent elements in a subarray. In examples shown in Fig. 1, the element spacing is *d* and the subarray spacing is *4d*.

The subarray output signals are converted into digital signals at baseband. Then, digital beamforming is performed to control the phase shifters in the subarrays as well as the weights associated with respective subarray output signals. The hybrid beamformer structure is illustrated in Fig. 2 using the linear array of two subarrays shown in Fig. 1 (a) [10].



(a) (b)

Fig. 1. Hybrid antenna arrays with (a) two linear subarrays and (b) four square subarrays, where *d* is the element spacing and different subarrays are shown in different fill patterns.

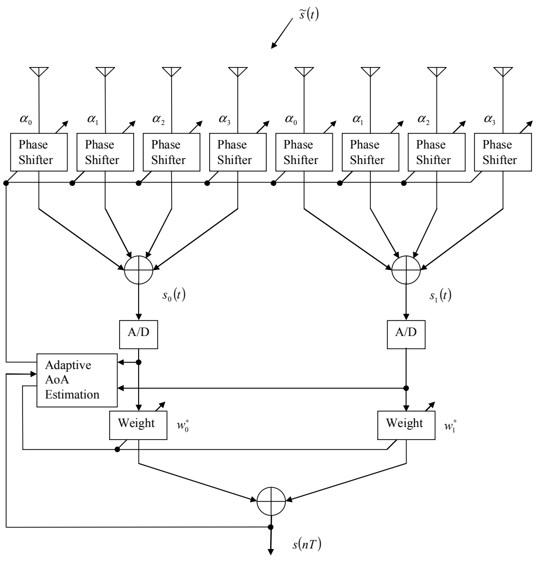


Fig. 2. Hybrid beamformer structure with two four-element linear subarrays.

B. Received Signal Models

Denoting the received signal of the *m*th subarray, $m=0,1,\cdots,M-1$, where M is the total number of subarrays, as $s_m(t)$, and the reference signal received at a virtual reference antenna element placed at the origin of the antenna array coordinate system as $\tilde{s}(t)$, the received subarray signal model can be expressed as

$$s_m(t)=\tilde{s}(t)\sum_{i=0}^{N-1}P_{i,m}(\theta,\phi)e^{j\left[\frac{2\pi}{\lambda_c}\left(X_{i,m}\sin\theta\cos\phi+Y_{i,m}\sin\theta\sin\phi\right)+\alpha_{i,m}\right]}+n_m(t),$$
$$m=0,1,\cdots,M-1, \qquad (1)$$

where N is the total number of elements in a subarray, $P_{i,m}(\theta,\phi)$ is the radiation pattern of the *i*th element located at $(X_{i,m},Y_{i,m})$ in the *m*th subarray, θ and ϕ are the zenith and azimuth angles respectively, λ_c is the wavelength of the RF signal, $\alpha_{i,m}$ is the phase shifted by the *i*th phase shifter of the *m*th subarray, and $n_m(t)$ is the total additive white Gaussian noise presented at the output of the *m*th subarray.

Furthermore, we assume that the radiation patterns and phases of the corresponding elements in different subarrays are the same respectively, i.e., $P_{i,m}(\theta,\phi)=P_i(\theta,\phi)$ and $\alpha_{i,m}=\alpha_i$. Also, we assume that the number of subarrays can be expressed as $M=M_x\times M_y$, where M_x and M_y are the numbers of subarrays placed along x-axis and y-axis respectively, and that the locations of the *i*th elements in the *m*th subarray, $m=m_yM_x+m_x$, are arranged such that $X_{i,m}=X_i+m_xd_x^s$, $m_x=0,1,\cdots,M_x-1$, and $Y_{i,m}=Y_i+m_yd_y^s$, $m_y=0,1,\cdots,M_y-1$, where d_x^s and d_y^s are the subarray spacings along x-axis and y-axis respectively, and (X_i,Y_i) is the location of the *i*th element of the subarray numbered $m=0$. Then, (1) can be simplified as

$$s_m(t)=\tilde{s}(t)P_s(\theta,\phi)e^{j\frac{2\pi}{\lambda_c}\left(m_xd_x^s\sin\theta\cos\phi+m_yd_y^s\sin\theta\sin\phi\right)}+n_m(t) \qquad (2)$$

where

$$P_s(\theta,\phi)=\sum_{i=0}^{N-1}P_i(\theta,\phi)e^{j\left[\frac{2\pi}{\lambda_c}\left(X_i\sin\theta\cos\phi+Y_i\sin\theta\sin\phi\right)+\alpha_i\right]} \qquad (3)$$

is the overall radiation pattern of a subarray. From (2) it is apparent that a subarray is equivalent to an element with radiation pattern $P_s(\theta,\phi)$ and its output signal experiences an additional phase shift which is related to the subarray location and the incident signal angles.

In general, a two-dimensional subarray has $N=N_x\times N_y$ elements, where N_x and N_y are the numbers of elements placed along x-axis and y-axis respectively. The location (X_i,Y_i) of the *i*th element, $i=i_yN_x+i_x$, is given by $X_i=X_0+i_xd$, $i_x=0,1,\cdots,N_x-1$, and $Y_i=Y_0+i_yd$, $i_y=0,1,\cdots,N_y-1$, where *d* is the element spacing and (X_0,Y_0) is the location of the element numbered $i=0$. The subarray spacings are thus $d_x^s=N_xd$ and $d_y^s=N_yd$ respectively.

Finally, denoting the weight applied to the *m*th subarray signal as w_m^*, the overall digital beam formed output signal at

$t = nT$, $n = 0,1,\cdots$, where T is the sampling period, is

$$s(nT) = \sum_{m=0}^{M-1} w_m^* s_m(nT). \quad (4)$$

III. AoA Estimation and Beamforming

A. Phase Ambiguity and Beam Scanning

From the subarray output signal model (2), we see that the AoA information, i.e., the angles θ and ϕ, is contained in the phase difference between the adjacent subarray output signals. Thus, by taking the cross-correlation of any two adjacent subarray output signals along x-axis and y-axis respectively and assuming that the noise components are independent, one has

$$\begin{aligned} R_x &= E\left\{ s_{m_y M_x + m_x}{}^*(t) s_{m_y M_x + m_x + 1}(t) \right\} \\ &= E\left\{ \left| \tilde{s}(t) \right|^2 \right\} \left| P_s(\theta,\phi) \right|^2 e^{j\frac{2\pi}{\lambda_c} d_x^s \sin\theta\cos\phi} \end{aligned} \quad (5)$$

$$\begin{aligned} R_y &= E\left\{ s_{m_y M_x + m_x}{}^*(t) s_{(m_y+1) M_x + m_x}(t) \right\} \\ &= E\left\{ \left| \tilde{s}(t) \right|^2 \right\} \left| P_s(\theta,\phi) \right|^2 e^{j\frac{2\pi}{\lambda_c} d_y^s \sin\theta\sin\phi} \end{aligned} \quad (6)$$

where $E\{\cdot\}$ denotes ensemble expectation.

We then define

$$u_x = (2\pi/\lambda_c) d \sin\theta\cos\phi \quad (7)$$

$$u_y = (2\pi/\lambda_c) d \sin\theta\sin\phi \quad (8)$$

which can be obtained from $\arg\{R_x\}/N_x$ and $\arg\{R_y\}/N_y$ respectively provided that d is sufficiently small so that the phases of R_x and R_y are in the range $[-\pi,\pi)$.

The quantities u_x and u_y contain the AoA information of the incident beam and can be used to determine the phase shifts in the subarrays, i.e., $\alpha_i = -(X_i u_x + Y_i u_y)/d$. The explicit values of the angles $-\frac{\pi}{2} \le \theta \le \frac{\pi}{2}$ and $-\frac{\pi}{2} \le \phi \le \frac{\pi}{2}$ are not required though they can be easily determined as $\theta = sign(u_x)\sin^{-1}\left(\frac{\lambda_c}{2\pi} \frac{\sqrt{u_x^2 + u_y^2}}{d} \right)$ and $\phi = tg^{-1}\left(\frac{u_y}{u_x} \right)$. The beam formed signal can be obtained accordingly as

$$s(nT) = \sum_{m_y=0}^{M_y-1} \sum_{m_x=0}^{M_x-1} e^{-j(m_x N_x u_x + m_y N_y u_y)} s_{m_y M_x + m_x}(nT) \quad (9)$$

after applying the digital weights $w_m^* = e^{-j(m_x N_x u_x + m_y N_y u_y)}$ to the subarray output signals.

In practice, the element spacing d is about $\lambda_c/2$. Therefore, the phases of R_x and/or R_y can be outside the range $[-\pi,\pi)$, and ambiguity will occur when $\arg\{R_x\}$ and $\arg\{R_y\}$ are used to determine the phases of R_x and R_y respectively.

To remove this ambiguity and thus obtain the right AoA information, one can find all the possible u_x and u_y values from $\arg\{R_x\}$ and $\arg\{R_y\}$ respectively, and try all the possible combinations of u_x and u_y, which represent all the possible beams, to see which combination gives the largest beam formed signal power. The u_x and u_y values corresponding to the largest beam formed signal power is used to obtain the AoA information.

All the possible u_x and u_y values can be determined respectively by $u_x(p) = (2\pi p + \arg\{R_x\})/N_x$, $p = -[N_x/2]$, $-[N_x/2]+1,\cdots,0,1,\cdots[N_x/2]$, and $u_y(q) = (2\pi q + \arg\{R_y\})/N_y$, $q = -[N_y/2], -[N_y/2]+1,\cdots,0,1,\cdots,[N_y/2]$, where [.] denotes the operation of taking the integer part of a value. Each combination of $u_x(p)$ and $u_y(q)$ is a possible beam.

To compare the signal powers of different beams, all possible beams are scanned within a period of time. We call this period of time the scanning frame. A scanning frame is divided into subframes for different combinations of p and q . Within each subframe, each beam formed signal power is calculated. At the end of a scanning frame, the beam with the largest signal power is decided as the estimated signal beam. The beam scanning frame and subframe are illustrated in Fig. 3 for a linear subarray with 5 elements ($N = N_x = 5$ and $N_y = 1$) and $\arg\{R_x\} = \frac{\pi}{3}$. In this example, there are 5 possible beams with $u_x(-2) = -\frac{11\pi}{15}$, $u_x(-1) = -\frac{\pi}{3}$, $u_x(0) = \frac{\pi}{15}$, $u_x(1) = \frac{7\pi}{15}$, and $u_x(2) = \frac{13\pi}{15}$. The scanning frame has 5 subframes and the beams are scanned from $u_x(-2)$ to $u_x(2)$ in order.

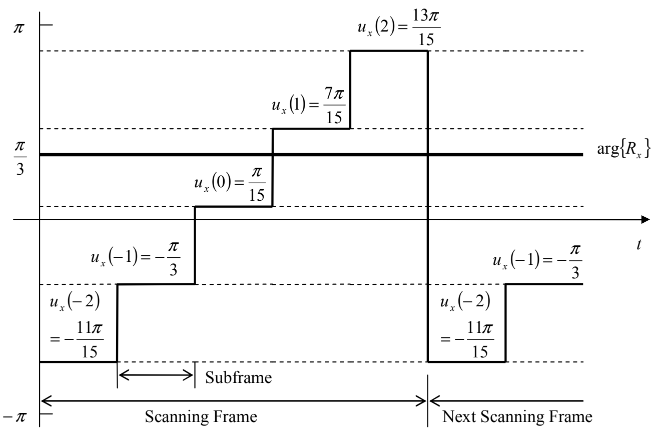


Fig. 3. Illustration of scanning frame and subframes.

B. Adaptive DBS Algorithm

In the digital domain, the cross-correlations along x-axis and y-axis can be estimated iteratively using the digital subarray output signals as

$$R_x^{(n)} = (1-\mu) R_x^{(n-1)} + \mu \sum_{m_y=0}^{M_y-1} \sum_{m_x=0}^{M_x-2} s_{m_y M_x + m_x}{}^*(nT) s_{m_y M_x + m_x + 1}(nT) \quad (10)$$

$$R_y^{(n)} = (1-\mu)R_y^{(n-1)} + \mu \sum_{m_x=0}^{M_x-1}\sum_{m_y=0}^{M_y-2} s_{m_yM_x+m_x}{}^*(nT)\, s_{(m_y+1)M_x+m_x}(nT) \quad (11)$$

where $0 < \mu < 1$ is the updating coefficient. All available subarray outputs are used for the cross-correlation estimation in order to improve SNR. The beam formed signal power can be iteratively estimated in a subframe as

$$P^{(n)}(p,q) = (1-\beta)P^{(n-1)}(p,q) + \beta|s(nT,p,q)|^2 \quad (12)$$

where $0 < \beta < 1$ is the updating coefficient, and $s(nT,p,q)$ is the beam formed signal calculated by (9) using $u_x(p)$ and $u_y(q)$ obtained at $t = nT$, denoted as $u_x^{(n)}(p)$ and $u_y^{(n)}(q)$ respectively.

Combining these iterations (10), (11), and (12) with the beam scanning scheme, we have the adaptive algorithm, called the differential beam search (DBS), which proceeds in a subframe for a given combination of p and q as follows at the *n*th iteration.

1. Update $R_x^{(n)}$ and $R_y^{(n)}$;
2. Calculate $u_x^{(n)}(p) = \left(2\pi p + \arg\{R_x^{(n)}\}\right)/N_x$ and $u_y^{(n)}(q) = \left(2\pi q + \arg\{R_y^{(n)}\}\right)/N_y$;
3. Determine $\alpha_i^{(n)}(p,q) = -\left(X_i u_x^{(n)}(p) + Y_i u_y^{(n)}(q)\right)/d$;
4. Update $s(nT,p,q)$ and $P^{(n)}(p,q)$;
5. Select p and q for next subframe.

Since the above algorithm uses the phase difference between adjacent subarray output signals to obtain the beam's AoA information, it is a blind algorithm since no knowledge about the reference signal $\tilde{s}(t)$ is required.

If the length of a subframe is chosen so that the power of each beam can be calculate with sufficient accuracy, one scanning frame will be sufficient to determine the most likely beam. If shorter subframes are used, the scanning frame can be repeated until the power of each beam calculated across multiple scanning frames is obtain with sufficient accuracy. Once the correct beam is determined, the algorithm will be locked to the selected beam, i.e., the p and q will be fixed, and it proceeds to the beam tracking stage with steps 4 and 5 being skipped.

IV. Simulation Results

The proposed AoA estimation and beamforming algorithm is simulated using a hybrid array of four side-by-side subarrays as shown in Fig. 1 (b). Each subarray has 16 elements arranged as a 4 by 4 matrix and there are 2 subarrays placed along x-axis and y-axis respectively. The element spacing is half of the signal wavelength, i.e., $d = \lambda_c/2$. The incident angles of the received signal are set to 40 degree in zenith and 0 degree in azimuth, corresponding to $u_x = 2.0194$ and $u_y = 0$ respectively. The SNR per antenna element is set to -10 dB. The reference signal is a realization of a Gaussian distributed complex random signal.

The simulation results using DBS with updating coefficients $\mu = 0.001$ and $\beta = 0.25$ for the hybrid array of side-by-side subarrays are shown in Fig. 4 to Fig. 8. The correct $\arg\{R_x\}$ and $\arg\{R_y\}$ values are 1.7943 and 0 respectively. The possible u_x values are -2.6930, -1.1222, 0.4486, 2.0194, and 3.5902, and the possible u_y values are -3.1416, -1.5708, 0, 1.5708, and 3.1416. There are total 25 different beams to scan, so there are 25 subframes in one scanning frame. The number of samples in one subframe is set to 4 in the simulation and thus one scanning frame has 100 signal samples. Fig. 4 depicts the estimated $\arg\{R_x\}$ and $\arg\{R_y\}$ versus the number of iterations respectively for 4 scanning frames. Fig. 5 shows the u_x and u_y values when the beams are sequentially scanned. Fig. 6 shows the estimated signal powers for all beams during the beam scanning. It is observed that the peak power in each scanning frame appears when the beam with the fourth value of u_x and the third value of u_y is scanned, and thus this beam is chosen as the correct one. The peak power will approach the average beam formed signal power as the beam scanning proceeds (with possible fluctuation due to the signal variation and the presence of noise). Finally, Fig. 7 and Fig. 8 show the normalized array factors for a subarray and the hybrid antenna array respectively after 4 scanning frames. The estimated u_x and u_y values are 1.9701 and -0.02206 respectively which correspond to 38.84 degree in zenith and -0.64 degree in azimuth. It is seen that the estimated AoAs are very close to the true values and the beamwidth of the hybrid antenna array is sharpened after digital beamforming.

V. Conclusions

A new hybrid antenna array of subarrays and the associated beam search and adaptation algorithm, the differential beam search (DBS), are proposed to significantly simplify the implementation of adaptive antenna arrays at mm-wave frequencies, and to reduce the digital signal processing cost. The DBS algorithm can blindly estimate the AoA information of the hybrid antenna array with side-by-side subarrays, and perform digital beamforming. It can be used not only for initial beam acquisition, in which all possible beams are scanned and the corresponding beam formed signal powers are compared, but also for beam tracking once the correct beam is locked. The performance of the DBS algorithm is demonstrated by simulation. Combined with the advanced AoA estimation and beamforming algorithm, the hybrid antenna array of subarrays enables long range, high data rate, mobile and ad hoc mm-wave communications and is well suited for practical implementation.

References

[1] Y. Jay Guo, *Advances in Mobile Radio Access Networks*, Artech House, Inc., 2004.

[2] Frank B. Gross, *Smart Antennas for Wireless Communications*, McGraw-Hill, 2005.
[3] D. Rogstad, A. Mileant, and T. Pham, *Antenna Arraying Techniques in the Deep Space Network*, Wiley-IEEE, 2003.
[4] H. Meinel, "Commercial Applications of Millimeterwaves History, Present Status, and Future Trends," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 43, No. 7, July 1995, pp. 1639-1653.
[5] J. I. Agbinya, et al, *Advances in Broadband Communication and Networks*, River Publishers, 2008.
[6] H. Zirath, T. Masuda, R. Kozhuharov and M. Ferndahl, "Development of 60-GHz Front-End Circuits for a High-Data-Rate Communication System," *IEEE Journal of Solid-State Circuits*, Vol. 39, No. 10, October 2004, pp. 1640-1649.
[7] C. H. Doan, S. Emami, D. A. Sobel, A. M. Niknejad, and R. W. Brodersen, "Design Considerations for 60 GHz CMOS Radios," *IEEE Communications Magazine*, Vol. 42, No. 12, December 2004, pp. 132-140.
[8] T. Do-Hong and P. Russer, "Signal Processing for Wideband Smart Antenna Array Applications," *IEEE Microwave Magazine*, March 2004, pp. 57-67.
[9] R. J. Mailloux, "Subarray Technology for Large Scanning Arrays," *The Second European Conference on Antennas and Propagation* (EuCAP2007), 11-16 November 2007.
[10] Y. Jay Guo, John Bunton, Val Dyadyuk, and Xiaoing Huang, "Hybrid Adaptive Antenna Array," Australian Provisional Patent 2009900371, February 2009.

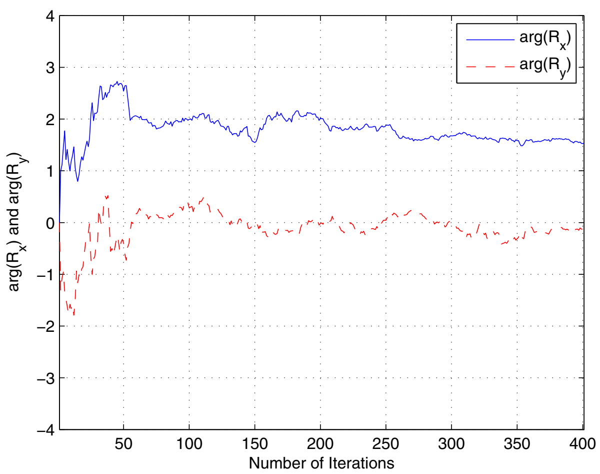


Fig. 4. Estimated phases of cross-correlations versus the number of iterations using DBS for hybrid array of side-by-side subarrays.

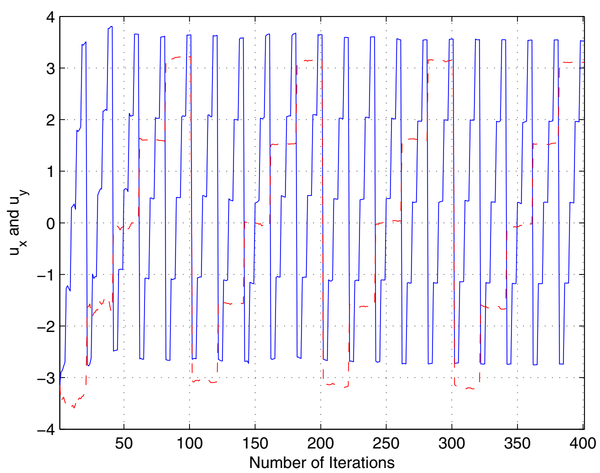


Fig. 5. Beam search via u_x (solid line) and u_y (dashed line) scanning.

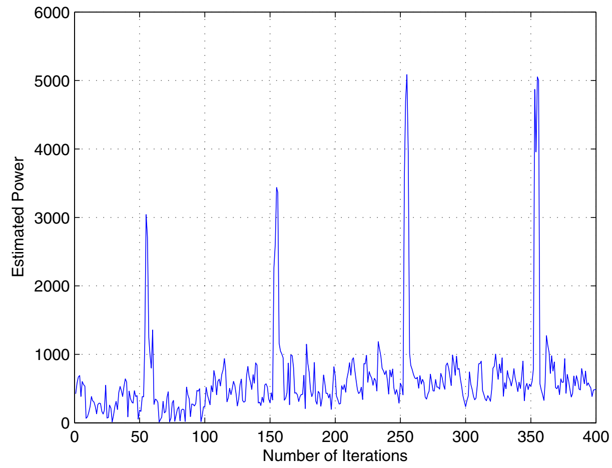


Fig. 6. Power profile of different beams. Peak power indicates the correct beam.

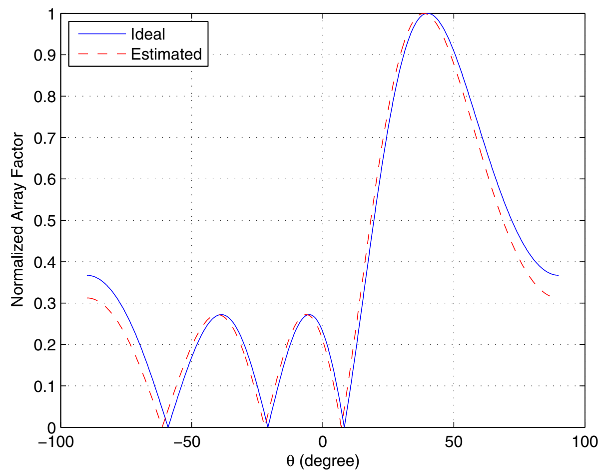


Fig. 7. Normalized array factor for a subarray ($\phi = 0$).

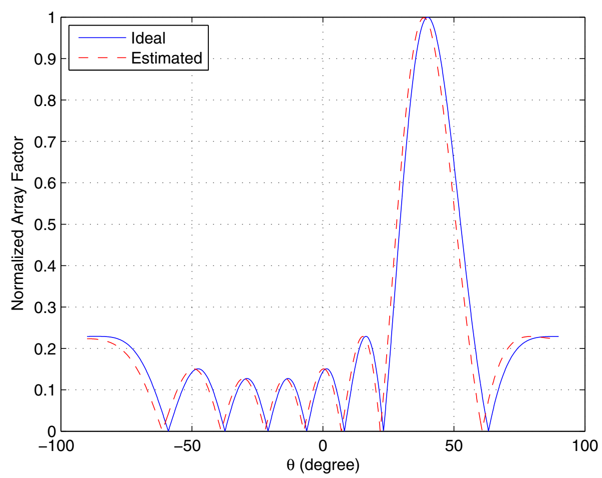


Fig. 8. Normalized array factor for hybrid antenna array ($\phi = 0$).