Chapter 4
DOA Estimation Using Adaptive Array Antenna in the 2-GHz Band

4.1. Introduction

The demands for wireless mobile communication are increasing rapidly, and they have become an indispensable part of our lives. More information must be transferred rapidly not only to provide seamless communications in indoor systems such as wireless LANs but also to provide flexible communications in outdoor communication systems. However the frequency spectrum is a finite resource, so if the faster transmission of large information is required, the newly techniques that use it more effectively must be developed.

The use of array antennas is a promising approach. Co-channel interference and multipath fading are reduced because a transmitter or receiver with an array antenna can increase or decrease the antenna gain in intended directions. As a result, the channel capacity, quality of service (QoS), and transmission rate can all be increased [1]. Array antennas have therefore recently been put to practical use in the base stations (BS) of the personal-handypone-system (PHS).

In order to realize beam control at BS according to the users’ positions, it is important to know the directions of arrival (DOA) of signals at the BS. By knowing the DOA from MSs, BS can suitable beam control. This DOA-based method requires the calculation of the DOA estimation and weight adaptation independently. Popular algorithms for DOA estimation and weight adaptation have been summarized in Ref. [2].

The reliability of the DOA estimation at BS is very important in the DOA-based beamforming control because the beam-pattern resulting from the DOA-based beamforming depends on the estimation of the DOA. Therefore, investigating the performance of DOA estimation in various areas is very important in order to implement the DOA-based
beamforming control in wireless communication systems. However, there are few studies that provide discussions on the accuracy of DOA estimation in various environments through experiments. Reference [3] reported characteristics of DOA and time-of-arrival (TOA) in 25GHz-band in the environment of an urban area, and the accuracy of estimated DOAs was analyzed by using a ray-trace method. The ray-trace method which was used in [3] seems to be an effective tool for investigating the accuracy of estimated results in 25-GHz band since the intensity of the signals attenuates immediately by a few reflections or diffractions because of the characteristics of the frequency. However, in 2-GHz band, the intensity of the signals that were affected by reflection or diffraction does not attenuate so much compared with the 25-GHz band. Therefore, it is difficult to implement the ray-trace method for the investigation in the 2-GHz band because uncountable reflection signals and diffraction signals between the transmitter and receiver cause the complexity in calculation. Moreover, the reflection or diffraction signals that have relatively high power cause the problem of not only the analytical investigation but also the experimental results, since they can lead to serious errors in DOA estimation.

On the other hand, Ref. [4] and [5] showed the effect of DOA-based beamforming control through the experiments at 2-GHz band. From the viewpoint of the improvement of bit-error-rate (BER) of a signal from a moving transmitter, ref. [4] and [5] reported the effects of DOA-based beamforming. Reference [4] reported the DOA-based beamforming for the GSM system and Ref. [5] reported the DOA-based beamforming for the W-CDMA system. They showed the large improvement of BER of received signals using DOA-based beamforming, however, they do not mention about the accuracy of estimated DOA.

In order to improve the BER performance effectively in the system with DOA-based beamforming, the experimental investigation of the accuracy of estimated DOA in various environments is important in 2-GHz band. Moreover, it is essential to investigate the reliability
of estimated DOAs in urban area, although it is difficult to obtain their accuracy. The experimental results can give the valuable information to construct the systems that use the DOA-based control.

In this chapter, the author focused on the investigation about the accuracy of estimated DOAs using 8-element array antenna in the 2-GHz band, which is extremely in demand for wireless communications. The configuration of the developed equipment is reported, then the performance of DOA estimation for incoherent signals and coherent signals are examined, respectively, in anechoic chamber. Based on the above results, the experimental results for the DOA estimation in outdoors (non-multipath and multipath environments) are shown. On the multipath environment in outdoor, the reliability of estimated DOAs is also investigated from the viewpoint of BER improvement by forming the beam.

Furthermore, the performance of the DOA estimation for moving mobile with high speed is also reported. In order to treat moving mobiles, a new scheme which based on the combination of MUSIC (MUltiple SIgnal Classification) or ESPRIT (Estimation of Signal Parameters via Rotational Invariance Techniques) and the fast DOA-tracking algorithm [6] are proposed, and the performance of the DOA estimation is confirmed experimentally.

This chapter is organized as follows. Section 4.2 describes the equipment the author developed, Sections 4.3 and 4.4 report the experimental results obtained in an anechoic chamber and outdoors. Section 4.5 concludes by summarizing the chapter and mentioning some further work that needs to be done.

4.2. Experimental System

4.2.1 Overview of the Developed Prototype

The experimental adaptive array system is shown in Fig. 4.1(a), the block diagram of the system is shown in Fig. 4.1(b), and the system parameters are listed in Table 4.1 [7]. The
system consists of an array-antenna block, a frequency-conversion block, and a
digital-processing block. The array antenna has eight microstrip patch antennas, separated
from each other by a distance equal to half the wavelength of a 2.335-GHz wave. Dummy
elements are placed at both ends of the array block to equalize the characteristics of the
element. The antenna pattern of an element (#7) is shown in Fig.4.2(a). The beam pattern in
the specific directions are shown in Fig.4.2(b). The 2.335-GHz RF signals received are
converted to 450 kHz by down-converters and analog filters in the frequency-conversion
block. The IF signals are sent to the digital-processing block, which consists of
analog-to-digital (A/D) converters, a DOA estimation block, a weight-adaptation block, and a
beamforming block. The IF signals are digitized by the A/D converters, which have a 12-bit
resolution, and the digitized IF signals are converted to the I and Q base-band signals. The
data bus transfers the I/Q channel data to the DOA-estimation, weight-adaptation, and
beamforming blocks. The DOA-estimation block uses one of three types of DOA estimation
algorithms: multiple signal classification (MUSIC) [8], estimation of signal parameters via
rotational invariance techniques (ESPRIT) [9], or a fast DOA-tracking algorithm. The
weight-adaptation block calculates the optimum weight vector based on the estimated DOA,
and the beamforming block synthesizes the signals received at each element using the
calculated weight vector. Because of the narrow bandwidth of the base band signal (42kbps),
the sampling rate of 200kHz is enough to keep the information of the signal. On the other
hand, the 1.8 MHz sampling rate corresponds to the four times of the frequency of the IF
signal to keep the IF signal itself. Since each block can be operated independent of the others,
thus, it is able to investigate the DOA algorithms and the beamforming control, independently.
Table 4.1. System parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
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<tbody>
<tr>
<td>RF frequency</td>
<td>2.335 GHz</td>
</tr>
<tr>
<td>Modulation</td>
<td>$\pi/4$-shift QPSK, 42 kbps</td>
</tr>
<tr>
<td>Array antenna</td>
<td>8-element linear array</td>
</tr>
<tr>
<td>Antenna element</td>
<td>Microstrip antenna</td>
</tr>
<tr>
<td>IF frequency</td>
<td>450 kHz</td>
</tr>
<tr>
<td>AD converter 1</td>
<td>12 bit, 1.8 MHz</td>
</tr>
<tr>
<td>DOA estimation</td>
<td>MUSIC, ESPRIT</td>
</tr>
<tr>
<td>DOA tracking</td>
<td>Fast DOA-tracking algorithm</td>
</tr>
<tr>
<td>Weight adaptation</td>
<td>DCMP</td>
</tr>
<tr>
<td>AD converter 2</td>
<td>12 bit, 200 kHz</td>
</tr>
<tr>
<td>Demodulation</td>
<td>Delay detection</td>
</tr>
</tbody>
</table>
control part 8-element linear array antenna.

(a) Components

(b) Configuration of the experimental system.

Fig. 4.1. Adaptive array antenna equipment
(a) The antenna pattern of a element (#7)

(b) The beam pattern for the specific directions (-90 ~ 0 degrees).

Fig. 4.2. The characteristics of antenna pattern.
4.2.2. DOA Estimation Algorithms

The following problems are considered for the DOA estimation at BS using the 2-GHz band.

1) DOA estimation for a signal from users that are stopped or moving slowly.

2) DOA estimation for a signal from moving users with large angle changing at high speed.

The case 1) includes not only the case that the signal-to-noise ratio (SNR) is relatively high but also the case that SNR is low. The later case occurs when a user is far from the BS or at non-line-of-sight (NLOS) from the BS. On the other hand, the case 2) occurs when the users move by a car around the BS. Although the case 2) also includes both of the case that the SNR of the received signals is high (LOS environment) and the case that the SNR is low (NLOS environment), in this chapter, the author studies the case that a user moves on LOS.

Most conventional algorithms for estimating the DOA are based on the calculation of the autocorrelation matrix of the received signals and the analysis of the eigen structure of its matrix. They obtain the results with high accuracy even for signals with relatively low SNR, though they require a large amount of calculation time. The accuracy of the result degrades when the users move fast because the DOA estimation is obtained on the assumption that the received signals are stationary. Therefore it is thought that this type of algorithms are suitable for the case 1).

The recursive type algorithms, which do not use a correlation matrix of received signals to calculate the DOA, have been also proposed for DOA estimation. Their accuracy of DOA for fixed users is inferior compared with the former algorithms, but they can maintain the accuracy of estimation results for the moving users. Therefore it is thought that this types of algorithms are suitable for the case 2).
In this study, MUSIC and ESPRIT are implemented in order to correspond to the case 1). A space smoothing preprocessing (SSP) scheme [10] is also applied to MUSIC or ESPRIT algorithm so that estimation error could cope with the multipath environment. Furthermore, in order to correspond to the case 2), a recursive algorithm is adopted, namely, a fast DOA-tracking algorithm which maintains high accuracy of the DOA estimation for the moving users. Since the fast DOA-tracking algorithm requires the initial value of angular velocity and angle for the DOA calculation, the author proposes the scheme which combines the fast DOA-tracking algorithm and a MUSIC or ESPRIT.

In the experiment, the calculation of DOA estimation for a moving transmitter is done as follows:

1) The transmitter position is estimated as the initial value given by MUSIC or ESPRIT.

2) The fast DOA-tracking algorithm is used to calculate the DOA and velocity at sampling time $t$.

3) $t$ is set to $t+1$, and the calculation return to step 2). When 1000 repetitions are finished, the calculation return to step 1).

The flowchart of the DOA estimation block is shown in Fig. 4.3. The experimental results using this scheme are reported in sec. 4.3.

By using the equipment, MUSIC or ESPRIT requires about 70 ms to calculate one estimation when the number of samples is 1024, and the fast DOA-tracking algorithm requires about 0.7 ms to calculate one estimation.
4.3. Experimental Results of DOA Estimation in an Anechoic Chamber

First, the performance of the DOA estimation using ESPRIT algorithms for incoherent signals is examined, then the DOA estimation for coherent signals is examined. Throughout the experiments, 1024 samples are used for the calculation of ESPRIT.

4.3.1. DOA Estimation for Incoherent Signals [11]

The array antenna was set on a turntable as a receiver (Rx). The experiments are performed under two different conditions. In condition I, a single transmitter was set in front of the array antenna. In condition II, two transmitters were used. The configurations of these experiments are illustrated in Fig. 4.4, where $\theta$ is the angle of the turntable and $\theta=-90$ and $\theta=90$ are defined as shown. In the experiments the transmission power of transmitter 1 (Tx1) and transmitter 2 (Tx2) was set so as to receive the signals at the same level at Rx. The distance between Tx1 and Rx was 10 m. Tx1 transmitted a modulated signal, and Tx2 transmitted a nonmodulated (carrier) signal.

The accuracy of the DOA estimation in condition I is shown in Fig. 4.5(a). In condition II
the two transmitters in front of the array antenna were located at an interval of $\phi$ degrees. Figure 4.6(a)(b) show the results when $\phi = 5$ and 20, respectively. Figure 4.6(c) shows the maximum value between the estimation errors for Tx1 and those for Tx2. The DOA estimation error increased as $\phi$ became smaller.

To evaluate the performance of DOA estimation under typical outdoor conditions, it was also examined when the height of the Tx1 antenna was lower than that of the Rx antenna, since it was thought that a BS was usually above mobile stations. The angle of elevation between the Tx1 and Rx antennas was about 7 degrees. Figure 4.5(b) shows the estimated results and Fig. 4.5(c) shows the estimation error when the evaluation angles were set to 0 degree and 7 degrees. The results showed that the equipment could estimate the reliable DOA when $|\theta| \leq 60$ degrees, though the estimation of the DOA became less accurate when $|\theta|$ was large.
(a) Result of DOA estimation in condition I when the elevation angle was 0 degree.

(b) DOA estimation results in condition I when the elevation angle was 7 degrees.

(c) The estimation error when the elevation angle was 0 degree and 7 degrees.

Fig. 4.5. Result of DOA estimation in condition I.
(a) $\phi = 5$

(b) $\phi = 20$

(c) The maximum estimation errors between the results of Tx1 and Tx2.

Fig. 4.6. Result of DOA estimation in condition II.
4.3.2. DOA Estimation for Coherent Signals [12]

To examine the accuracy of DOA estimation for coherent signals, multiple transmitters were connected to the same signal generator. The generated signal was divided, and then connected to a channel simulator that can control the time-delays and signal attenuation, individually.

The Rx was set on a turntable. The experiments were performed under two more conditions. In condition III two transmitters were set in front of the array antenna, and in condition IV three transmitters were set in front of the array antenna. The structure of the transmitters for condition IV is shown in Fig. 4.7. The power of all the transmitters were set to the same value. The distance between Tx1 and Rx was 12 m.

The results of DOA estimation using ESPRIT with SSP (SS-ESPRIT) for coherent signals without time-delays that were sent in condition III (\(\phi = 10\) and 15) are shown in Fig. 4.8. For the DOA calculation, the number of sub-array equivalency was set to six. On the analysis of DOA estimation using sub-array, the reduction of the size of correlation matrix causes the deterioration of estimation accuracy [13]. Therefore the DOA experiments were performed three times for each direction to confirm the stable characteristics in cases III and IV. As shown in Fig. 4.8(a)(b), the DOA estimation was less accurate when \(\theta\) increased or \(\phi\) decreased. Fig. 4.8(c) shows the comparison of the estimation errors between the experimental results (indicated by ‘×’) and the simulation results (indicated as the surface). The simulation were performed under the condition of an 8-element array antenna with 6 sub-array size, where SNR = 8 dB. The deterioration of the accuracy of the DOA was also observed when \(\theta\) and \(\phi\) change in the simulation. As shown in the figure, the experimental results slightly deteriorate compared with the ideal results. It is thought that the deterioration was due to the disagreement between characteristics of antenna elements.

The DOA estimation for delayed signals was also examined by assigning a delay to the Tx2 signal: 0.2 symbols, 0.5 symbols, 1 symbol, and 2 symbols. The average of root-mean-square
error for each direction when $\phi = 10$ is shown in Fig. 4.9. When the symbol delay was 0 or 0.2, the error increased when $\theta$ became large. Particularly, when the symbol delay was 0.2, the a reliable DOA estimate did not obtained when $\theta$ was more than 30 degrees. When the symbol delay of Tx2 was greater than 1, the equipment could estimate the direction of each transmitter accurately.

The results of DOA estimation in condition IV when $\phi = 15$ are shown in Fig. 4.10. As similar to the case III, the accuracy deteriorated as $\theta$ became larger. Next, the DOA accuracy was examined in the case where the signals from Tx2 and Tx3 were delayed compared with the signal from Tx1 (center transmitter). The averages of root-mean-square errors of the estimation for each transmitter are shown in Fig. 4.11. As similar to the case III, the results showed that the root-mean-square error deteriorated as the symbol delays became smaller.

Finally, the BER performance of the system was examined when two signals arrived with different delays. The BER performance of received signals which received by one element (no array control) are shown in Fig. 4.12. The transmission powers for Tx1 and Tx2 were the same. When array control was not used, the BER increased as the symbol delay became larger.
(a) Transmitter position.

(b) Transmitter configuration.

Fig. 4.7. Experimental configuration in condition IV
(a) $\phi = 15$

(b) $\phi = 10$

(c) The estimation errors obtained by the experimental results and simulation results.

Fig. 4.8. Result of DOA estimation in condition III
Fig. 4.9. Root-mean-square error when $\phi = 10$ (condition III).

Fig. 4.10. Result of DOA estimation in IV.
Fig. 4.11. Root-mean-square error when $\phi = 15$ (condition IV).
4.3.3. Considerations

From the experiments in anechoic chamber, the author found the following:

1) When a signal arrived at the array, the almost accurate DOAs were estimated within $|\theta| \leq 60$ degrees.

2) When two incoherent signals arrived, the roughly accurate DOAs were estimated within $|\theta| \leq 60$ degrees even $\phi = 5$ degrees.

3) When coherent signals arrived at the array via multiple paths, the DOA was estimated less accurately compared with the case that incoherent signals arrived. The accuracy of DOA estimation improved as the difference of the delays between arrival signals became large.

4) If the antenna received two signals with different delays, the BER deteriorated as the difference of the delays became large.

The results of 1) and 2) show that the equipment would be an effective tool for finding the DOAs of the incoherent signals arrived. On the other hand, in a multipath environment where coherent signals exist, it is thought that signals with large delays will tend to come from close directions, and signals that are delayed greatly will tend to come from another direction, because of the differences in DOAs. Therefore, from the result of 3), the reliable DOA
estimation is expected for the signals arrived from different directions with different delay-times. Although it is difficult to isolate the directions of signals that arrived from near directions, having near delays, it is important to isolate signals with different delay-times from the viewpoint of the BER improvement. The result of 4) shows that the delayed signal behaves like a interference.

4.4. Experimental Results Obtained Outdoors

In this section, the experimental results obtained outdoors were reported. Firstly, the performance of DOA estimation for incoherent signals in nonmultipath environment and then that for coherent signals in multipath environment were examined. Using the proposed procedure explained in subsec. 4.2.2, the DOA estimation for moving users with 40 km/h was also examined. Throughout the experiments, 1024 samples were used for the calculation of MUSIC and ESPRIT. The results obtained by these algorithms were also almost same, so the author only shows the results by ESPRIT in subsections 4.4.1 and 4.4.2.

4.4.1. Experiment in Rural Area (DOA Estimation for Incoherent Signals) [11]

Figure 4.13 shows the configuration of the outdoor experiments. Across the road from the array antenna was a coppice, so few of the transmitted signals were reflected. The the array antenna was positioned parallel to the street and slightly higher than the road bed. Given the results obtained in the anechoic chamber, the accuracy of DOA estimation was examined over the range between –60 and 60 degrees. Within this range, the maximum angle of elevation from the street to the antenna was about 12 degrees and the minimum angle was about 3 degrees.

Two conditions were examined, one was when a single transmitter (Tx1) was used, and the other was when two transmitters (Tx1 and Tx2) were used. Tx1 transmitted a modulated
signal and Tx2 transmitted a carrier signal. Tx1 was positioned at several points in order to change the DOA of its signal. At each point the transmission power level was set so that the signals had the same level at the Rx antenna. Tx2 was fixed at the position of 20 degrees. Figure 4.14(a)(b) shows the results of the DOA estimation with one transmitter and with two transmitters, respectively. The DOA was estimated almost perfectly within 5 degrees.

Fig. 4.13. Configuration of outdoor experiments (rural area).
(a) DOA estimation when one transmitter was set.

(b) DOA estimation when two transmitters were set.

Fig. 4.14. DOA estimation in a rural area

4.4.2 Experiment in Urban Area (DOA Estimation for Coherent Signals) [12]

Figure 4.15 shows the ground plan in urban area. The experimental system was mounted on the top of a building 13 m high. The height of the array antenna was about 15 m. The height of most of surrounding buildings were more than 20 m. The transmitter was set at the position of A (LOS) or B (NLOS) as shown in Fig. 15. The distances from the array antenna to the positions of A and B were about 215 m. The angles obtained by the map for A and B are –12 degrees and –57 degrees, respectively. The angle of elevation from each position to the array
antenna was less than 10 degrees. The number of sub-arrays was set to five in the DOA calculation of MUSIC with SSP (SS-MUSIC) and SS-ESPRIT. These algorithms require the “number of arriving signals” although the true “number of arriving signal” is unknown in practice. A suitable value for the “number of arriving signals” has to set for a reliable DOA estimation because the estimated DOA varied with the value.

One of the results of DOA estimation for position A and B, respectively, are listed in Table 4.2(a) though the estimated DOA changed by the setting value of the “number of arriving signals” for DOA calculation. The estimation results for A included -9.6 degrees, which was very close to the actual angle -12 degrees. The estimation results for B, however, did not include a value close to the actual angle -57 degrees.

To confirm the reliability of the estimated DOAs, the BER improvement was investigated by using beamforming control. The beam was shaped every 10 degrees between –60 to 60 degrees using phase control. The weight vector of the array was set as

\[ w = [1, \exp(j\xi\sin\theta), \ldots, \exp(j\xi(M-1)\sin\theta)]^T, \]

where \( \xi = 2\pi d / \lambda \), \( d = \lambda / 2 \), and \( \theta_i \) is the target direction.

Fig.4.15. Configuration of outdoor experiments (urban area).
### Table 4.2. (a) Estimated direction of arrival.

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-39.2**</td>
<td>-9.6*</td>
<td>27.4</td>
</tr>
<tr>
<td>B</td>
<td>-40*</td>
<td>30**</td>
<td></td>
</tr>
</tbody>
</table>

### Table 4.2. (b) The BER performance when directing the phase for each direction

| Direction | -60   | -50   | -40   | -30   | -20   | -10   | 0     | 10   | 20   | 30   | 40   | 50   | 60   |
|-----------|-------|-------|-------|-------|-------|-------|-------|------|------|------|------|------|------|------|
| A         | 3.7E-02 | 4.7E-03 | 8.2E-03 | 1.7E-02 | 8.7E-06 | 0.0E+00 | 2.6E-05 | 1.1E-02 | 5.8E-02 | 1.7E-01 | 2.6E-03 | 7.8E-03 | X    |
| B         | 3.3E-04 | 5.6E-05 | 5.1E-05 | 1.9E-03 | 1.9E-02 | 3.8E-02 | 7.3E-02 | 1.4E-02 | 1.0E-02 | 4.0E-03 | 8.2E-03 | 1.2E-02 | 1.5E-03 |

The results are listed in Table 4.2(b). As for A, the BER was smallest at around -10 degrees, and the BER around -40 degrees was also relatively small though the BER around 27.4 degrees was not small. As for B, on the other hand, the BER was smallest at around -40 degrees, and the BER around 30 degrees was also relatively small. The results showed that the directions that had low BER almost corresponded with the estimated directions.

However, the arrived signal usually contains the delayed signal, which sometimes behave like interference. In order to confirm the characteristics of arrival signals, the BER performances were compared in the following three cases:

Case 1: the array received the signal with a single element.

Case 2: the array received the signal with 8-elements by using phase control. The direction $\theta_1$ for the main beam was defined by the estimated DOA that best improved the BER performance (the direction is marked ‘*’ in Table 2(a)).

Case 3: the array received the signal and the weight vector was calculated by a directionally constrained minimization power (DCMP) algorithm [14]. The direction for the main beam was defined by the estimated DOA that best improved the BER performance (‘*’). The direction that improved BER performance the second best was set as the null direction (‘**’).

Here, the author briefly explains the DCMP algorithm implemented in the equipment.
Using 1024 samples, the weight vector was calculated recursively, in order to solve $w$ of the equation, $C^T w = h$, where $C = [e(\theta_1) e(\theta_2)]$ is a matrix of array responses for the constraint direction, $e(\theta_j) = [1, \exp(j\xi \sin \theta_{1j}), \cdots, \exp(j\xi (M-1) \sin \theta_{1j})]^T$, and $h = [h_1, h_2]$ is the vector of the complex-valued gain for the constraint directions, $\theta_1$ and $\theta_2$. The value of $h_1$ as 1 and $h_2$ were set as 0.

The BER performances for each direction are shown in Fig. 4.16. For position A, the BER was improved by using phase or DCMP control compared with Case 1. This is because the signal from –9.6 degrees was dominant signal between whole of arrival signals. Therefore the beamforming for –9.6 degrees improved BER effectively. On the other hand, for position B, the BER was improved by more than 10 dB with phase control and by about 5 dB with DCMP control. It means that there was a time lag between the arriving signals from -40 and 30 degrees and the power of each signal was almost same. Therefore, the weight control directing a beam for the direction from which a strong multipath signal arrived and directing null for the direction where other multipath signal arrived improved the BER effectively because the delayed signal behaved like a interference. The variation in measured values shown in Fig. 4.16 should be caused by the reflections from other moving vehicles in the experimental area.
4.4.3. Estimation of the DOA of a Moving Transmitter [11,15]

Finally the reliability of estimated DOA using the combination of MUSIC or ESPRIT and the fast DOA-tracking algorithm was examined in the rural area and in the urban area. In the rural area shown in Fig.4.13, a vehicle (Tx1) moved down the street at 40 km/h. The accuracy of the DOA estimation is shown in Fig. 4.17, where squares show the results calculated by ESPRIT and the solid line shows the results calculated by the fast DOA algorithm. The crosses show the actual positions calculated from the time and velocity. This figure indicates that the fast DOA-tracking algorithm is extremely accurate. When Tx1 moved within ±60 degrees in front of the array antenna, the maximum error was about 10 degrees, and when Tx1
moved within ±20 degrees, the maximum error was about 3 degrees.

On the other hand, in the urban area shown in Fig. 4.18, the array antenna was mounted on the top of a building 60 m above the ground. The width of the road on which was used for experiment was about 20 m and the average height of the buildings along the road was more than 20 m. A vehicle was driven at 40 km/h along the road in front of the building on which the antenna was mounted. For the experiment, the start and end positions of the course were defined as shown in Fig. 4.18, in order to keep LOS between Tx1 and array antenna. The elevation angle was less than 10 degrees over the entire course. The distance between the start position and the antenna was about 562 m, and the distance between the end position and the antenna was about 242 m. The respective start and end positions were -15.7 and –17 degrees from the antenna. MUSIC was used to calculate the initial value, and the results are shown in Fig. 4.19. The figure shows that the fast DOA-tracking algorithm estimated the DOA to be almost –16 degrees. However, as shown in Fig. 4.19, the accuracy deteriorated compared with the case of the rural area.

![Fig. 4.17. DOA estimated with a fast DOA-tracking algorithm.](image-url)
Fig. 4.18 Configuration of experiments using a fast DOA-tracking algorithm (urban area).

Fig. 4.19. DOA estimated using MUSIC and fast DOA-tracking algorithm.

4.4.4. Considerations

The author obtained the following results through the experiments:

1) Rural area (nonmultipath environment): The almost accurate DOAs were estimated for
incoherent arrival signals.

2) Urban area (multipath environment): The estimated DOAs for multipath signals had meaning in the improvement of BER performance. The estimated DOA for multipath signals can be useful for improving the BER performance.

3) The proposed scheme for the DOA estimation obtains reliable results when the transmitter moves at a speed of 40 km/h in LOS environment.

The result of 1) concerns the reliability of DOA estimation using the 8-element array antenna in a nonmultipath environment. From the result of 3), the results showed that the proposed method could realize the high-accuracy and high-speed DOA calculation in LOS environments. For further works, it is required the study for DOA estimation of the signals from a moving transmitter in a NLOS environment.

As for the results of 2), following considerations were obtained:

- LOS propagation in an urban area: The receiver observed that multiple signals including the direct and reflected or diffracted waves arrived from one transmitter. However, the beamforming control for the direct wave was able to improve the BER sufficiently because the direct wave was stronger than the multipath waves.

- NLOS propagation in an urban area: The receiver observed that multiple signals without direct wave arrived from one transmitter via various paths. The power of the arriving waves was low and there was a time-lag depending on the length of each path between the arriving signals. Therefore, directing the antenna beam in the direction of a strong multipath signal and directing nulls in the direction of the other multipath signals could improve the BER effectively because the difference in the delays between the received signals caused the deterioration of BER.

From the viewpoint of the BER improvement, it is important to estimate the DOA of the direct wave accurately in a LOS environment. On the other hand, not only estimation DOA
for the multipath waves but suppressing or synthesizing of the delayed waves effectively is also important for the BER improvement, in NLOS environment. To put the DOA estimation to practical use for beamforming, however, the author need to study for discrimination of the profitable DOA from the estimated DOAs. Moreover, the author need to study for finding the number of actual arrival coherent signals in order to obtain more accurate results if MUSIC or ESPRIT is used for the DOA estimation. Low accuracy is allowable for the estimated DOAs because the width of synthesized beam has relatively broad width for the target direction as shown in Fig. 2 (b).

The beamforming control based on the reliable estimated DOAs of up-link signals improves the QoS of up-link signal effectively. It leads saving consumption powers of the mobile terminals. Moreover, if the frequency of the up-link and down-link is close, the estimated DOAs of up-link signal also used for the down-link beamforming in order to improve the QoS of down-link signal. However, when the frequency of down-link differs from that of up-link, it is difficult to use the estimated DOAs of up-link signal for directing nulls toward to the unnecessary signals because a few difference of direction degrades the attenuation of the unnecessary signals.

4.5. Conclusion

In this chapter the author reported experimental results on DOA estimation in 2 GHz band using the linear array antenna with an 8-element. The performance of DOA estimation in nonmultipath and multipath environments were examined. The applied DOA estimation algorithms for fixed transmitters were SS-MUSIC and SS-ESPRIT. For a moving transmitter, the combination of MUSIC or ESPRIT and the fast DOA-tracking algorithm was applied. The experiments for evaluation of the performance of the equipment were conducted in an anechoic chamber in the sense of the accuracy of the DOA estimation. Then the experimental
was performed in outdoors. In non-multipath environment, the 8-element array antenna could estimate accurate DOAs. In multipath environment, the results showed that appropriate beamformings based on the estimated DOAs could improve the BER performance. The results also showed that the proposed scheme could obtain the reliable DOA estimation for a moving transmitter at 40 km/h.

Further work will include investigations under multipath environments with multiple transmitters.