

Estimation of the Incoming Wave Characteristics by MUSIC Method Using Virtual Array Antenna

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ABSTRACT

Traditionally, the suitability of radio receivers and similar devices for automotive use has been evaluated by evaluating their reception characteristics in relation to transmitted waves via repeated driving tests. This method of evaluation presents issues in terms of reproducibility and objectivity. A method of evaluating the suitability of FM receivers for vehicle fitting using a virtual propagation environment created on a PC (termed the Two-Stage method) has been developed in order to address these issues.

The major challenge in the Two-Stage method is the creation of an actual propagation environment on a PC. A test-based incoming wave estimation technology able to accurately estimate the characteristics of actual propagation environments is therefore essential.

The estimation of incoming FM waves necessitates large array antennas. In addition, the incoming waves become coherent multipath waves. It is challenging to separate multipath waves, and this represents an issue for accurate estimation.

Seeking to address these challenges, the research discussed in this paper developed a Multiple Signal Classification (MUSIC) method using a virtual array antenna. The developed method has made it possible for the first time to accurately estimate arrival direction and delay time in an actual FM radio wave environment.

Spatial smoothing preprocessing (SSP) and modified spatial smoothing preprocessing (MSSP) were applied to the virtual array antenna in order to boost performance in separating incoming waves. This made it possible to freely combine array element numbers and subarray element numbers, helping to enable decorrelation, and thus increasing the method's performance in separating multipath waves.

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INTRODUCTION

The Two-Stage method, in which a virtual propagation environment is created on a PC, has been developed in order to provide a tool for evaluating the suitability of FM radio receivers for fitting in vehicles [1].

The major technological challenge in the Two-Stage method is gaining a grasp of propagation environment characteristics using transmitted FM waves. A test-based method of estimating incoming waves able to accurately estimate propagation environment characteristics including the number, arrival direction, delay time, and desired signal to undesired signal ratio (DUR) of incoming FM radio waves is therefore essential.

The MUSIC method [2, 3, 4], which uses array antennas, is one method for estimating incoming waves, and has the advantage of being able to simultaneously estimate arrival direction and delay time. However, the following issues make it challenging to apply this method to FM:

1. The number of antennas is high, and the array antenna is large
2. If the antenna spacing is narrow, a large electromagnetic coupling effect occurs
3. Compensation for antenna element and active element scattering takes time
4. The frequency characteristics of the transmission frequencies make estimation of delay time challenging

Seeking to respond to these issues, the research discussed in this paper developed a MUSIC method using a virtual array antenna [5, 6, 7, 8]. The developed method has made it possible for the first time to simultaneously estimate the number, arrival direction, and delay time of incoming waves.

In this method, a directional antenna is positioned in an area with a good reception environment for direct waves as a reference antenna, while a non-directional measurement antenna is moved. The reference signal and measurement signal received from the respective antennas are recorded simultaneously using an RF recorder. During playback, the correlation between the respective antenna signals is determined, and MUSIC processing is applied. This technique presents the following advantages:

1. No array antenna is necessary
2. There are no restrictions on antenna spacing
3. The time spent on calibration can be reduced
4. Delay time can be estimated with no effect from transmission frequency characteristics

In cities and other heavily built-up environments, FM broadcast waves are reflected off buildings and become coherent multipath waves. Thus, it has been difficult to separate multipath waves, and this has represented a challenge for accurate estimation of incoming waves.

Attempting to resolve this issue, the research discussed in this paper combined a virtual array antenna and MSSP [9, 10], from which a high level of decorrelation performance can be expected, thus helping to enable decorrelation suitable to actual environments and increasing the method's performance in separating multipath waves.

Because the virtual array antenna method is a technique in which the measured antenna is moved while its signals are recorded by an RF recorder, it is a simple matter to increase the array element number. It is therefore possible to freely create combinations of array and sub-array element numbers during playback. The application of these combinations to MSSP makes it possible to find the optimum conditions for separation performance in actual environments.

The MUSIC method using a virtual array antenna has therefore made it possible to estimate incoming FM radio waves, which was previously an issue.

During testing of the method in Bakersfield using an FM broadcast frequency of 95.3 MHz, it was possible for the first time to simultaneously estimate arrival direction and delay time. In order to accurately estimate arrival direction and delay time via the MUSIC method using a virtual array antenna, the operation of the MUSIC algorithm using the virtual environment propagation model was verified in advance.

ESTIMATION OF ARRIVAL DIRECTION OF FM BROADCAST WAVES USING MUSIC METHOD

Papers have been published previously concerning the estimation of the arrival direction of radio waves [11]. The most basic method is the beamforming method, which uses the same principle as Fourier transformation.

A variety of methods are available for the measurement of delay time, including Fourier transformation (frequency sweep methods) and measurement methods that exploit the acute self-correlation characteristic of M sequence and other pseudo noise (PN) codes (pulse compression methods) [12]. However, the former have low resolution, and the latter necessitate the use of special equipment. Neither type of method displays sufficient resolution with regard to arrival direction and delay time, and neither is able to simultaneously estimate these parameters. By contrast, the MUSIC method displays good resolution with regard to both parameters, and is capable of simultaneous estimation. The MUSIC method was therefore applied in the research discussed here.

Principle of Estimation of Arrival Direction Using MUSIC Method

The MUSIC method makes use of the characteristics of array antennas [2, 3, 4]. Figure 1 shows a basic equally-spaced linear array antenna. For an antenna element number M and an antenna element spacing of d , with each antenna non-directional, it is hypothesized that the reception characteristic of all the antennas will be equivalent. The incoming wave is incident as a planar wave from the direction of angle θ . Here, taking $x_1(t)$, the signal received by antenna element #1, as the reference, due to the spatial positioning of the antenna elements, there is a distance difference of $d\sin\theta$ in propagation paths for neighboring antennas. Given this, a radio wave of propagation speed C_0 will be received by the m^{th} antenna element with a delay time of τ_m only, as shown by Equation (1).

$$\tau_m = (m-1)d\sin\theta/C_0 \quad (1)$$

Here, terming the wavelength of the incoming wave λ and its frequency f , the relationship $C_0 = f\lambda$ exists. Using this relationship in Eq. (1) gives Eq. (2).

$$\tau_m = (m-1)d\sin\theta/\lambda \quad (2)$$

Thus $x_m(t)$, the signal received by the m^{th} antenna element, can be expressed by Equation (3) using $x_1(t)$, the signal received by antenna element #1.

$$x_m(t) = x_1(t - \tau_m) \quad (3)$$

Actual broadcast waves have an occupied bandwidth, B_w , rather than a unitary frequency like Eq. (2). However, when the occupied bandwidth is narrow, there are considered to be no changes of phase within the band, and it can therefore be treated in the same way as a unitary frequency.

The principle of estimation of arrival direction using the MUSIC method can be interpreted as follows: The null points within the directionality pattern of an array antenna possess acute directionality. If the direction of arrival can be detected using these null points, it will be possible to estimate an accurate direction of arrival.

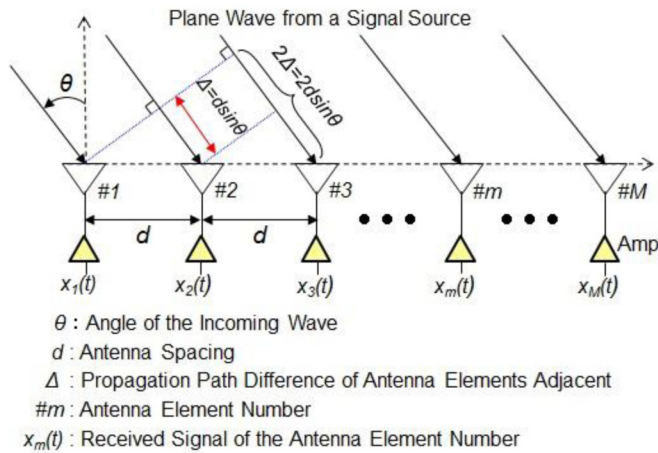


Figure1. M Element Equally Spaced Linear Array Antenna

Principle of Estimation of Delay Time Using MUSIC Method

By contrast with the estimation of arrival direction, which uses an array antenna positioned in the space shown in Fig. 1, the estimation of delay time uses a virtual frequency array antenna [2, 3, 4]. Figure 2 shows a conceptual diagram of the frequency array. For the estimation of arrival direction, $x_1(t)$, the signal received by antenna element #1 in Fig. 1, is employed as the phase reference. When delay time is being estimated, the time of arrival (TOA) of a direct wave from the broadcasting station is employed as the reference.

The frequency array uses the occupied bandwidth of the broadcast waves, B_w . For example, from Figure 2, if the occupied bandwidth, B_w , is divided into M_f units at a constant interval of Δf , the number of frequency arrays is M_f . Based on sampling theorem, if data in the frequency domain is sampled at equal intervals of Δf , the maximum delay time that can be estimated, T_{MAX} , is

$$T_{max} = 1/\Delta f = M_f/B_w \quad (4)$$

When the length of an array antenna formed by M antenna elements can be ignored in comparison with the distance between the points of transmission and reception, the delay time detected at each antenna is considered to be identical. Therefore, it is possible to obtain the same results of delay time estimation with any measurement antennas.

The same algorithms that are employed in the estimation of arrival direction can be employed in the estimation of delay time.

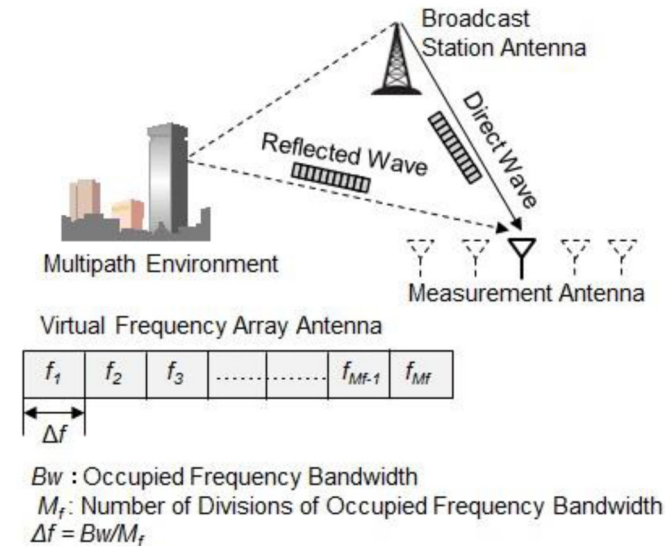


Figure 2. Conceptual Diagram of Frequency Array by Frequency Division of Occupied Bandwidth

Principle of SSP and MSSP

Because the propagation environment assumed in the research discussed here was a multipath environment with identical broadcast waves as the wave source, the incoming waves reciprocally become coherent multipath waves. When all of the incoming waves are coherent multipath waves, rank becomes 1, and only a single signal eigenvalue is visible to methods like the MUSIC method that use eigenvalue expansion. It therefore appears that a single incoming wave is received, and it is impossible to estimate the correct number of incoming waves and their arrival direction. SSP and MSSP are methods of addressing this issue [9, 10]. Their objective is the recovery of full rank from a state of degeneration down to rank 1.

With regard to the principle of SSP, because coherent waves differ depending on the reception position, if the reception points are translated in parallel and the correlation values determined, the cross correlation value is reduced by the averaging effect, and it becomes possible to separate coherent waves. Normally, multiple subarrays with the same alignment are isolated from the entire array without physically moving the array antenna, and their subsequent correlation matrices are averaged. Figure 3 shows the isolation of $N (=M-K+1)$ elements while displacing each element of K subarray elements in a linear array made up of M elements. Terming the number of incoming waves L , the necessary condition for rank recovery using SSP in order to achieve accurate estimation is

$$N = M - K + 1 \geq L \quad (5)$$

The condition for application of MUSIC is

$$K \geq L + 1$$

