

Incoming Wave Estimation Characteristics by MUSIC Method Using a Virtual Array Antenna in Urban Reception Conditions

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ABSTRACT

We developed “Two-Stage Method” that makes it possible to evaluate the automotive suitability of FM receivers by generating a virtual radio wave environment on a PC. The major technological challenge for the Two-Stage Method was reproducing an actual radio wave environment on PC. It was necessary to estimate the characteristics of the FM radio wave environment in tests using the Multiple Signal Classification (MUSIC) method. However, when the MUSIC method is applied to FM reception, restrictions in factors including the number of array antenna elements and the occupied bandwidth result in issues of separation performance in relation to multipath waves in urban environments.

We therefore developed a MUSIC Method using a virtual array antenna, making it possible to create combinations of numbers of array and sub-array elements as desired, thus boosting multipath wave separation performance. This development was reported at the 2015 SAE World Congress.

However, this report did not offer verification of the accuracy of the method in estimating radio wave environment characteristics.

The research discussed in this paper therefore assumed cases of non-modulation and maximum modulation of the occupied bandwidth of the FM broadcast waves during estimation of delay time, and studied the effect of the occupied bandwidth in an urban environment. In addition, the reception environment in an actual urban area was modeled using 3D maps and ray tracing, and the arrival directions of FM waves were calculated numerically, verifying the accuracy of MUSIC method estimation. This demonstrated the usefulness and novelty of the research.

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INTRODUCTION

We developed the Two-stage method, in which a virtual radio wave environment is generated on a PC to evaluate the suitability of FM receivers for automotive applications, in order to realize a tool for the evaluation of FM radio receivers offering both reproducibility and objectivity [1].

The issue in using the Two-stage Method was understanding radio wave characteristics in an actual reception environment using FM broadcast waves. This necessitates a method of estimating arrival waves that makes it possible to accurately estimate radio wave environment characteristics including the number, direction of arrival (DOA), time of arrival (TOA) and desired signal to undesired signal ratio (DUR) of incoming FM broadcast waves based on tests.

The MUSIC Method using an array antenna [2, 3, 4] is available as a method of estimation of incoming waves. This method makes it possible to simultaneously estimate arrival direction and delay time. However, when the MUSIC Method is used in the estimation of incoming waves in a reception environment using actual broadcast waves, a large number of antenna elements is necessary, increasing the length of the array. Reduction of the intervals between antenna elements also increases the strength of electromagnetic coupling, weakening the directivity of the antenna. In addition, the correction of variations between large numbers of antenna elements and active elements is a time-consuming process. These and other issues have made the practical use of the method challenging.

In order to address these issues, Dr. Karasawa et al. developed a MUSIC method using a virtual array antenna, and proposed its use in the simultaneous estimation of the number of incoming waves,

arrival direction and delay time of terrestrial digital broadcast waves in an actual reception environment [5, 6]. However, the application of the method was limited to linear systems with a broad occupied bandwidth in which there were no changes in amplitude or frequency, such as digital broadcast waves. In addition, there was no discussion of the method's separation performance in relation to multipath waves in urban environments.

The authors therefore developed and reported on a MUSIC Method using a virtual array antenna that could be applied to nonlinear systems such as analogue FM broadcast waves [7, 8]. This method also made it possible to boost separation performance in relation to multipath waves in urban areas by freely combining the number of array elements and sub-array elements. However, the reports referenced above were published in the absence of verification of the accuracy of the method in estimating arrival direction and delay time.

The research discussed in this paper therefore assumed cases of non-modulation and maximum modulation of the occupied bandwidth of the FM broadcast waves during estimation of delay time, and studied the effect of the occupied bandwidth in an urban environment. The reception environment in an actual urban area was also modeled using 3D maps and ray tracing, and the arrival directions of FM waves were calculated numerically, verifying the accuracy of MUSIC Method estimation in an actual environment.

In addition, the research showed that the reduction of the intervals between the measurement antennas from the standard $\lambda/4$ to $\lambda/8$ enhanced separation performance in relation to arrival direction in multipath environments.

The application of this method to radio wave environments in urban areas has enhanced separation performance in relation to multipath waves, making it possible to estimate sources of reflection in urban environments. In addition, numerical calculations using ray tracing have demonstrated the effectiveness of the method in actual radio wave environments for the first time. These results demonstrated the usefulness and novelty of the method in relation to the estimation of incoming FM broadcast waves in urban environments.

Using an FM broadcast frequency of 80 MHz (Tokyo FM), broadcast waves transmitted from Tokyo Tower were received on the campus of the Tokyo University of Marine Science and Technology. It was possible to estimate the arrival direction and delay time of waves reflected from high-rise buildings and other obstacles in the vicinity. This paper will report on these results.

ESTIMATION OF DOA OF FM BROADCAST WAVES USING MUSIC METHOD

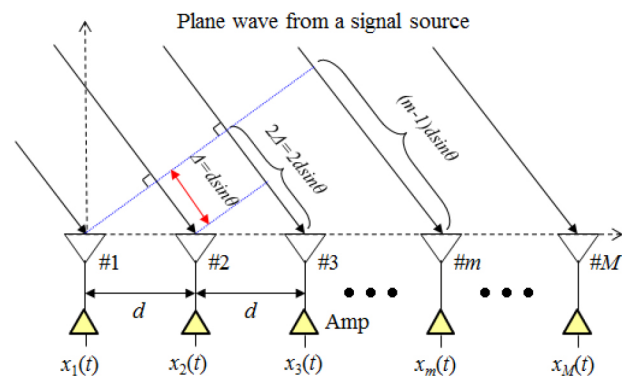
Papers have been published previously concerning the estimation of DOA of radio waves [11]. The most basic method is the beam-forming method, which uses the same principle as Fourier transformation.

A variety of methods are available for the measurement of TOA, 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 , as shown by Equation (1).



θ : Angle of incoming wave

d : Antenna spacing

Δ : Propagation path difference between adjacent antenna elements

$\#m$: Number of antenna element

$x_m(t)$: Received signal for number of antenna elements

Figure 1. M element equally spaced linear array antenna

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

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

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

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.

Principle of Estimation of TOA 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.

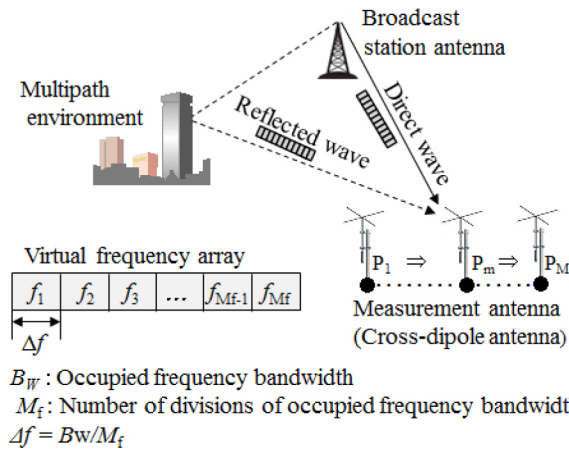


Figure 2. Conceptual diagram of the frequency array by frequency division of the occupied bandwidth

The frequency array uses the occupied bandwidth of the broadcast waves, B_w . For example, from Fig. 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, $\tau_{\max}$, is

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

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.

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 sub-arrays 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 sub-array elements in a linear array made up of M elements.

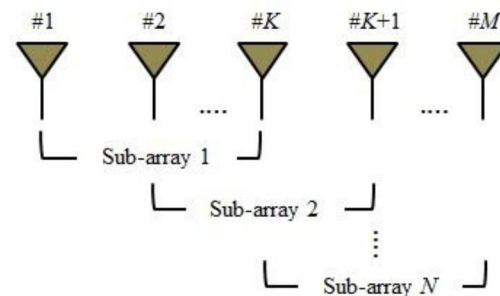


Figure 3. Relationship of K sub-array elements in M -element linear array

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

$$K \geq L + 1 \quad (6)$$

Therefore, from the inequality of the above two expressions,

$$M = N + K - 1 \geq L + K - 1 \geq 2L \quad (7)$$

The method therefore has the shortcoming that accurate estimation of the incoming waves using SSP necessitates a number of antenna elements twice the number of incoming waves. MSSP was devised as a method of correcting SSP. An advantage of MSSP is that it features two averaging procedures, in forward and reverse directions. Because the number of elements of the space average is $2N$, the rank recovery condition for MSSP is

$$2N \geq L \quad (8)$$

Therefore, from $K \geq L + 1$

$$M = N + K - 1 \geq L/2 + L \geq 3/2L \quad (9)$$

MSSP is therefore able to achieve a good de-correlation effect using fewer antenna elements than SSP.

Principle of MUSIC Method using a Virtual Array Antenna

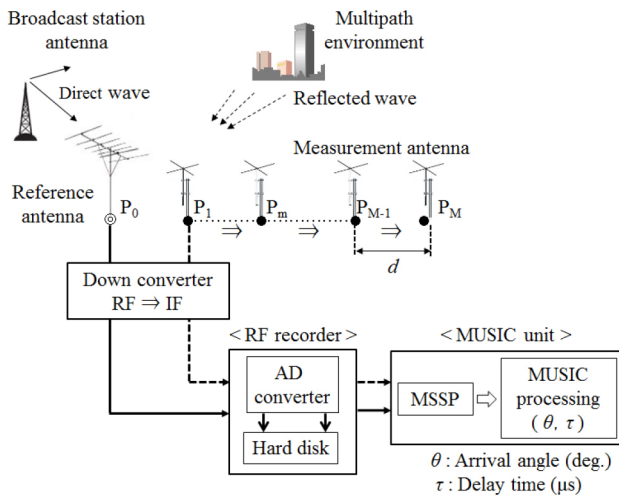


Figure 4. Block diagram of MUSIC-MSSP method using array antenna

Figure 4 shows the principle of the method of estimating incoming waves using a virtual antenna array, combining an RF recorder and SSP or MSSP and MUSIC processing [5, 6, 7, 8]. A reference antenna is fixed at point P_0 , offering a clear reception environment, and a reference signal with a high signal to noise ratio (SNR) is received. At the same time, a measurement signal is received by a measurement antenna at P_1 . If the reference signal and the measurement signal are recorded simultaneously by the RF recorder while measurement antenna is moved, data regarding the phase and amplitude of the measurement signal in relation to the reference signal can be obtained. The MUSIC method using a virtual array antenna is therefore equivalent to the MUSIC method using a conventional array antenna.

When the length of the virtual array antenna can be ignored in comparison with the distance between the transmission and reception points, delay time can be estimated using only the signal received by the measurement antenna at any arbitrary point P_m . By applying offline SSP and MSSP processing to the data recorded by the RF recorder and calculating a correlation matrix, it is possible to separate the coherent incoming waves and accurately estimate arrival direction and delay time. The same algorithms can be used in the estimation of delay time as are used in the estimation of arrival direction.

MUSIC Method for FM Broadcast Waves: Issues and Countermeasures

As a characteristic of FM receivers, when a noise with a flat frequency characteristic is received, the higher frequency components, the greater demodulation output. For example, if the frequency components of a sound have their peak at 0.5 to 1 kHz, frequency components higher than that become smaller in inverse proportion to the frequency. Modulation at the broadcasting station in order to emphasize the high-frequency components in the modulation signal (known as pre-emphasis) and demodulation by the receiver to attenuate the high-frequency components (known as de-emphasis) make it possible to obtain a demodulation signal with an equivalently good signal to noise ratio (SNR). Figure 5 shows the pre-emphasis characteristic of a broadcasting station and the deemphasis characteristic of a receiver. The overall frequency characteristic is flattened, and the equivalent SNR is improved.

As indicated above, the SNR of FM transmission frequencies differ at high and low frequencies. Thus, the fact that the occupied bandwidth of the transmission frequency is used as the frequency array when delay time is estimated using the MUSIC method means that the method cannot be applied to FM without modification.

In order to address this issue, a frequency array from which the effect of the transmission frequency characteristic of the FM broadcast station had been eliminated was achieved by correlating the reference and measurement signals.

Figure 6 shows a correlation block diagram for the reference and measurement signals.

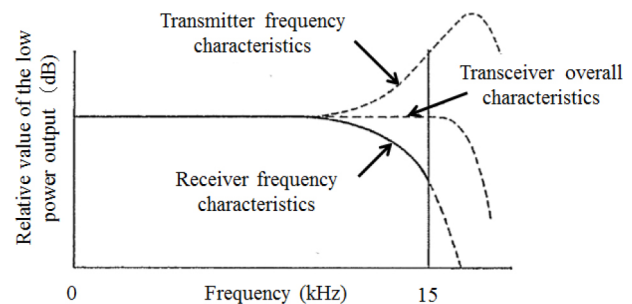


Figure 5. FM emphasis characteristics