Procedure of designing the structural parameters of a spatial fading emulator with a Laplacian angular power spectrum of incoming wave

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Abstract
This paper presents design procedure of a spatial fading emulator representing a Laplacian angular power spectrum of incoming wave applicable to the over-the-air (OTA) evaluation for a handset MIMO antenna. The emulator has a number of antenna probes located on a circle around a handset under tested. The radius of the circle arranging the antenna probes can be defined by the power ratio of waves emitted from each antenna probe. The number of the antenna probes can be determined by fading correlation of a two-dipole array. Moreover, the calibration procedure of an RF-controlled spatial fading emulator was also presented in this paper. The study presented in this paper was conducted under the collaboration between Tokyo Institute of Technology, Tokyo, Japan and Panasonic Corporation, Osaka, Japan.

1. Introduction
An RF-controlled spatial fading emulator can be applicable to a MIMO over the air (OTA) testing for incoming LTE and IMT-Advanced cellular radios [1]-[3]. The emulator can directly reproduce a multipath radio propagation environment in spatial domain by waves emitted from the antenna probes arranged around a handset tested. The emulator can vary not only a Doppler frequency but also a spatial distribution of the incoming waves. An effective area for the antenna testing is determined by a radius of a circle arranging the antenna probes and the number of the antenna probes. Moreover, in order to reproduce a narrow angular power spectrum (APS), such as the spatial channel model (SCM) [4] and the spatial channel model extended (SCME) [5] with a Laplacian distribution, a number of the antenna probes are needed. However, there is little study on design procedure for the Laplacian APS.

This paper presents a procedure of determining the structural parameters of the spatial fading emulator reproducing a multipath fading environment with the Laplacian APS of incoming wave. The determination procedure is shown as follows;

1. A radius of the emulator is defined by power ratio of waves radiated from the antenna probes.
2. The number of the antenna probe is determined by a fading correlation coefficient.

Firstly, determination procedure of the dimension of the spatial fading emulator is described in Section 2. Secondly, a calibration method of the RF-controlled spatial fading emulator before performing the MIMO OTA testing is shown in Section 3. Finally, in section 4, we conclude our study.

2. Determination of the dimension of spatial fading emulator representing a Laplacian APS
Figs. 1(a) and 1(b) show the configuration and arrangement of the antenna probes of the spatial fading emulator in an anechoic chamber [1], respectively. In Fig. 1, the emulator has 15 antenna probes in this
instance. The angular power spectrum $\Omega$ of the spatial cluster of incoming waves in the horizontal plane is modeled by a Laplacian distribution in the following:

$$
\Omega(\phi) = \frac{P}{2\sigma} \exp\left(-\frac{|\phi - \mu|}{\sigma}\right),
$$

where $P$ and $\mu$ are power and average direction of angle of the cluster. $\sigma$ is a standard deviation of the APS. The spatial distribution in the vertical plane is modeled by a delta function. The Laplacian distribution is widely used in the propagation models, such as SCM [4] and SCME [5]. In this section, we define the structural parameters of the emulator with regard to effective area for the MIMO OTA evaluation.

Fig. 2 illustrates the geometry for the fading emulator when the receiving antenna is set on the x-axis. We assumed that the antenna probes were set on the circle at regular intervals. In this case, the distance between the receiving antenna (Rx) and the antenna probe #1 is the smallest among all the distances. In the first step, we define the radius, $r$, of the emulator. Fig. 3 shows the power ratio of incoming wave emitted from each antenna probe in the case when the number of the antenna probe is 7. The wave power ratio ($P/P_o$) is defined as a ratio of the wave power, $P$, at the observation point Rx and that, $P_o$, at center of the emulator. $d$ is the distance between Rx and center of the circle. As can be seen from Fig. 3, $P/P_o$ in the case of the antenna probe #1 increases with an increase in $d/r$. In this paper, we defined the effective area with regard to the wave power by $P/P_o$ of less than 2 dB. In the case of 7 antenna probes, 2 dB increase in $P/P_o$ causes only 0.4 dB increase in the average received power of the fading signal and 0.3 dB errors at 1 % value of cumulative distribution of the received power of the Rayleigh distribution when the emulator produces uniform distribution of incoming waves. It is found from Fig. 3 that the effective area is obtained to be within a radius of 0.2$r$. It is obvious that for any number of the antenna probes $P/P_o$ in the case of the antenna probe #1 is the most significant of all. Thus, when the effective area with a radius of 0.3 m is desired, the radius of the circle of the emulator is needed to be more than 1.5 m, regardless of the number of the antenna probes.

In the second step, we determine the number ($L$) of the antenna probes by the effective area of correlation coefficient between the two antennas (Rx1 and Rx2). Rx1 is set at the center of the emulator and Rx2 is located on the x-axis. The theoretical correlation coefficient for discretely-distributed APS is obtained as an absolute value of the complex fading correlation calculated by the following equation [1]:

$$
\rho_L = \frac{\sum_{\phi_i}^{i} \Omega(\phi) \exp\{jkd \cos(\phi_i - \phi_p)\}}{\sum_{\phi_i}^{i} \Omega(\phi)},
$$

where $k = 2\pi/\lambda$ and $\phi_p$ is the angle of Rx2 with respect to the x-axis. In the following investigation, $\phi_p$ was set at 0 and $\pi/2$. With regard to the APS, $\mu$ was set at 0.

Fig. 4 shows the correlation coefficient as a function of the number, $L$, of the antenna probes in case of the Laplacian APS when the Rx2 is located on the x-axis. In this case, $d$ was set at $\lambda/2$. The symbol ‘o’, shown in Fig. 4, is the number of the antenna probes obtained in the case when an absolute value of the difference between the correlations of the discretely-distributed APS and continuously-distributed APS cases is less than 0.1. It is found from Fig. 4 that the number of antenna probes required for the accurate measurement of correlation coefficient increases as the standard deviation, $\sigma$, of the APS decreases. Fig. 5 shows the correlation coefficient in case of the Rx2 located on the y-axis. As can be seen in Fig. 5, the stability of the correlation coefficient of the Rx2 located on the y-axis needs more antenna probes than that
of the x-axis case. From this, we decide that the number of the antenna probes can be determined the stability of the correlation in the case of the array located on y-axis.

Fig. 6 shows the number of the antenna probes required in the case of the correlation difference less than 0.1 as a function of the distance between Rx1 and Rx2 in case of a Laplacian distribution with $\sigma$ of 35 degrees. In addition, the results of a uniform distribution are also plotted in Fig. 6. It is observed form Fig. 6 that the number required for the narrow APS with a Laplacian distribution is more than that for the uniform distribution. Moreover, it is found that the 15 antenna-probe configuration provides the accurate evaluation for the array within a circle with a radius of less than 1.4 wavelengths, which corresponds to 0.21 m at 2 GHz, with a correlation error of 0.1 in the case of narrow APS with $\sigma$ of 35 degrees. For the 8 antenna-probe configuration, an antenna array with a radius of only less than 0.38 wavelengths can be evaluated in this accuracy.

3. Calibration method of the spatial fading emulator for the MIMO OTA testing

Fig. 7 illustrates a configuration of the RF-controlled spatial fading emulator using a wireless local area network (WLAN) system based on the IEEE 802.11n. In this system, we can evaluate a 2-by-2 MIMO OTA testing. In order to perform the calibration, we have to know values of the amplitude and phase of the RF signal between a transmitter and receiver. In Fig. 7, a wireless access point (WAP) and a mobile station (MS) are used as the transmitter and receiver, respectively. We describe the calibration method of the spatial fading emulator using the WLAN application in this paper. In the case of a cellular radio, a radio communication analyzer and a cellular handset terminal are used as a substitute for the WAP and MS, respectively.

With regard to the calibration, we can easily measure the amplitude and phase of the RF signal using a vector network analyzer. Thus, by replacing the WAP and MS to the network analyzer, the calibration can be directly done from the output port of the WAP to the input port of MS via air.

Fig. 8 shows photographs of the emulator and the antenna-probe unit. The antenna-probe unit consists of two half-wavelength dipoles crossing at right angles in order to represent a cross polarization power ratio (XPR), as shown in Fig. 8(b). Thus, the calibration is needed to be done for both the vertical and horizontal polarizations using a half-wavelength dipole and a slotted cylindrical antenna [6] as a receiving antenna for vertical and horizontal polarizations, respectively. Each antenna has an omni-directional radiation pattern in the horizontal plane, as shown in Fig. 9.

The calibration is carried out using the following procedure;
(1) A half-wavelength dipole for the receiving antenna is placed at the center of a circle arranging the antenna probes.
(2) A radio wave with vertical polarization is radiated only from a vertical dipole of the antenna probe #i ($i=1, 2, \ldots, L$), and then, the dipole at the center of the emulator can receive the wave. From this, we can obtain the amplitude and phase of the RF signal from the transmitter to the receiver via the vertical dipole of the antenna probe #i.
(3) The attenuator and phase shifter are adjusted so that the RF signals received by the dipole at the center have the same values in amplitude and phase.
(4) Secondly the slotted cylindrical antenna is placed at the center of the antenna probes located on the circle.
(5) A radio wave with horizontal polarization is radiated only from a horizontally-located dipole of the antenna probe #i ($i=1, 2, \ldots, L$). From the received signal from the antenna probe #i, we also obtain
amplitude and phase of the RF signal from the transmitter to the receiver via the horizontal dipole of the antenna probe #i.

(6) The attenuator and phase shifter are adjusted so that the RF signals received by the slotted cylindrical antenna at the center have the same values in amplitude and phase.

The calibration procedure above mentioned can be performed by using an electrical-controlled RF switch. Thus, the calibration of the emulator can be done automatically using a computer in our system. Once the calibration is finished, we can vary the attenuators in order to produce a special distribution of the incoming wave and to make a cross polarization power ratio (XPR). Moreover, we can set an initial phase to each antenna probe to create a multipath fading channel.

5. Conclusion
The procedure of determining the structural parameters of the spatial fading emulator with a Laplacian power distribution of incoming wave, which include a radius of a circle of the emulator and the number of antenna probes, was presented. From this, the radius of the emulator was defined to be 1.5 m so that the effective area is obtained within a circle with the radius of 0.3 m, from the point of view of the wave power ratio emitted from the antenna probes. Moreover, the number of the antenna probes was needed to be more than 15, with respect to the correlation coefficient. This results in the effective area within a circle with a radius of 0.21 m at 2 GHz. In addition, we presented a calibration method of the RF-controlled spatial fading emulator before performing the MIMO OTA testing. This enables us to make the MIMO OTA evaluation using the emulator more accurate.

References:
(a) Experimental setup               (b) Arrangement of the antenna probes

Fig. 1 Experimental setup of the spatial fading emulator.

Fig. 2 Geometry for the fading emulator with 7 antenna probes when the receiver is set on the x-axis.

Fig. 3 Power ratio of incoming wave emitted from each antenna probe when the emulator has 7 antenna probes.
Fig. 4 Fading correlation as a function of the number of the antenna probes, L, in case of the Rx2 on the x-axis. $d$ is 0.5 wavelength in case of a Laplacian distribution.

Fig. 5 Fading correlation as a function of the number of the antenna probes, L, in case of the Rx2 on the y-axis. $d$ is 0.5 wavelength in case of a Laplacian distribution.
Fig. 6 Number of the antenna probes required in the case of the correlation difference less than 0.1 as a function of the distance between Rx1 and Rx2 in case of a Laplacian distribution with $\sigma$ of 35 degrees and a uniform distribution.

Fig. 7 Measurement system using the spatial fading emulator for a 2-by-2 MIMO WLAN system.
Fig. 8 Photograph of the spatial fading emulator.

(a) Setup in a radio anechoic chamber
(b) Antenna-probe unit

Fig. 9 Power gain patterns in the horizontal plane of (a) vertical polarization of a dipole, and (b) horizontal polarization of a slotted cylindrical antenna.