Rice Channel Realization for BAN Over-The-Air Testing Using a Fading Emulator with an Arm-Swinging Dynamic Phantom

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SUMMARY This paper presents a new methodology for realizing a Rice channel in BAN Over-The-Air (OTA) testing using a fading emulator with a dynamic phantom. For the proposed apparatus to be effective, the fading emulator must be provided with an appropriate K-factor that represents the actual propagation environment indoors. Further, an implementation of the Rice channel to the proposed fading emulator in BAN situation is presented. Thereafter, a calibration method for the fading emulator to adjust the actual K-factor of the on-body Rice channel is advanced. This calibration method is validated by analyzing the variations in the instantaneous K-factor attributed to the arm-swinging motion. Finally, an experiment is conducted for a continuous human walking motion with the fading emulator using an arm-swinging dynamic phantom. The results show that the developed fading emulator allows BAN-OTA testing to replicate the actual Rice channel propagation environment with the consideration of the dynamic characteristics of human walking motion.

key words: BAN-OTA testing, Rice channel, fading emulator, K-factor, dynamic phantom

1. Introduction

Over-The-Air (OTA) testing is a method of evaluating the general performance of a mobile device [1]. An OTA test to assess a multiple-input multiple-output (MIMO) handset antenna in multipath environments has been developed [2]–[4]. The study in [3] confirmed that the Rayleigh propagation environment indoors can be realized by setting a collection of random phases for the uniformly distributed scatterers. However, the OTA technique was not applied to body area network (BAN) systems in previous studies [5], [6]. In BAN systems, antenna characteristics are significantly altered by human body coupling or shadowing effects, and also the propagation environment. The determination of the actual performance of BAN terminals in specific use scenarios is a complicated subject. Therefore, in this study, our objective is aimed at developing an OTA methodology using a fading emulator for the accurate testing of BAN systems.

There are two major differences between an OTA test for cellular MIMOs and that for BAN radios. The first difference is that in BAN radios, we must consider dynamic channel variations, commonly referred to as shadowing, caused by the motion of an operator, such as the swinging of arms while walking. The second difference is that a BAN sensor module may be attached to the human body, such as on the head, torso, wrist, ankle or other positions, for collecting medical information where there is a strong direct wave coming from the sensor module to an access point attached at the waist, as shown in Fig. 1. This situation creates a Rice propagation environment in combination with the fields reflected from the surrounding objects.

In order to resolve the first issue, many studies have been published. Body dynamics are shown to significantly affect fading properties [7]–[13]. Previously, we developed an arm-swinging dynamic phantom that can simulate the natural walking style of humans [5]. Using the phantom, shadowing-fading combined effects have been analyzed in [5], [6].

As for the second difficulty, there are also many related papers. A channel model for a wearable BAN based on the path loss model measured in an anechoic chamber is presented in [14]. However, the multipath component is not considered. Some studies for on-body propagation channels in a hospital environment are discussed in [7], [15]–[20]. Literature [7] proposed a statistical model for the on-body dynamic channel, which shows that the multipath bounces result in an additional energy contribution to the channel gain between two on-body antennas. The degradation of the Rice factor results in a fading statistic approaching a Rayleigh distribution (see Table 6 in [7]). However, these investigations have some drawbacks, such as low repeatability and accuracy because of the actual test persons and the specific measurement locations. Moreover, the K-factors shown in [20] indicate that the best-fitting statistical model depends on numerous parameters, such as the propagation channel, human subject, the antenna, and its orientation. Therefore, using the statistical channel model, it is dif-
ficult to conduct a precise evaluation of commercially available BAN devices in a specific use scenario. Thus, developing an experimental methodology and instrument that takes into account the combined effects caused by the direct path and multipath signals indoors, considering human dynamic characteristics, is an indispensable aspect of the evaluation of BAN radio systems, as will be illustrated later.

In this paper, a configuration of a fading emulator used for BAN-OTA testing is proposed in Sect. 2. The RF-controlled fading emulator has a simple structure with a limited number of scattering dipole antennas; hence, it can be used to create a realistic radio propagation environment indoors.

Based on the configuration of the BAN fading emulator, an implementation of Rice channel to the fading emulator considering human walking motion is presented in Sect. 3.

In Sect. 4, a method of calibration by setting the attenuators in the fading emulator to adjust the actual K-factor is presented. In order to confirm the proposed method, basic measurements have been carried out, as will be illustrated in parts A, B, C, D, and E of Sect. 4. It is confirmed that when calibration with respect to the K-factor is carried out for a certain position of the arms and a certain relative location of the two on-body antennas, the K-factor for other angles of the arm can be inferred from the direct and reflected radio wave components using the proposed method of calibration. The measured results of the instantaneous K-factor for each angle of the arm coincide well with the estimated value, indicating that the proposed method of calibration in the fading emulator is valid. Hence, the proposed method is useful for realizing an on-body Rice channel in BAN systems.

Finally, an experiment of the fading emulator where the human phantom is walking while simultaneously swinging both the arms is carried out. The measured results agree well with the analytical outcomes indicating that the actual Rice channel propagation environment considering dynamic characteristics of human walking motion can be realized in BAN-OTA testing, as will be presented in Sect. 5.

Section 6 summarizes some important conclusions derived from this paper and also gives some possible future extension of the studies.

2. Configuration of the BAN Fading Emulator

The proposed fading emulator for BAN-OTA testing is shown in Fig. 2. The arm-swinging dynamic human phantom [5] is located at the center of the fading emulator. The phantom can swing both the arms to emulate the shadowing effects whereas the scatterers comprised of dipole antennas surrounding the phantom are used to create the cross-polarized fading signals at the Doppler frequency of walking. The diameter of the fading emulator is 240 cm, and the height of each surrounding dipole antenna measured from the floor is 100 cm. The signals radiated from the scatterers are summed around the phantom, and the desired radio channel environment can be generated, as shown by the blue dotted arrows. Additionally, a dipole antenna attached to the human body, e.g., on the chest, simulating a sensor module creates direct waves towards a dipole antenna simulating an access point located at the waist, as shown by the red solid arrow.

The fading emulator has two attenuators, ATT1 and ATT2, as shown in Fig. 2. The former is connected to the dipole antenna attached to the human body to control the direct wave component $P_d$, and the latter is connected to the dipole antennas used as scatterers located in the horizontal plane to control the multipath field components $P_r$. Therefore, the direct to the scattered field power ratio can be controlled with these two attenuators. Moreover, the K-factor representing the indoor radio propagation environment can be set with regard to the actual on-body Rice channel for BAN-OTA testing. The method of calibrating the fading emulator using the attenuators will be described in Sect. 4.

3. Implementation of Rice Channel to a Fading Emulator

Based on the configuration of the BAN fading emulator described in Sect. 2, an implementation of the Rice channel using the Monte Carlo method [5], [6], [21] considering the human walking motion in a BAN situation is presented in this section.

In general, BAN communications are classified into two major categories based on the different operational bandwidth: narrow band and wide band systems. In a narrow band system, the frequency is operated at 400 MHz or 950 MHz, leading to a low bit rate of communication. A frequency of 400 MHz is usually used for an implanted BAN system, such as capsule endoscopy; 950 MHz is generally applied to wearable devices. In this paper, we focus on a narrowband system at 950 MHz for on-body BAN antenna
n evaluation, and thus the channel is considered to have a flat fading or time-invariant response in the absence of delay signals.

As shown in Fig. 3(a), the BAN Rice channel is assumed to be surrounded by \( N \) scatterers uniformly arranged in the azimuth direction.

Initially, we focus on the reflected wave components \( P_r \) [22], [23], which indicate the multipath radio wave propagation environment, as shown in Fig. 3(a). Assuming that the \( n \)-th path has a transfer function with vertical and horizontal components, its transfer function at the antenna can be given by

\[
\begin{align*}
    h_{Vn} &= \sqrt{\frac{XPR}{1 + XPR}} h_{n} E_V(\theta_n, \phi_n) \exp(j \varphi_{Vn}) \\
    h_{Hn} &= \sqrt{\frac{1}{1 + XPR}} h_{n} E_H(\theta_n, \phi_n) \exp(j \varphi_{Hn})
\end{align*}
\]  

(1)  

(2)

where \( E_V(\theta_n, \phi_n) \) and \( E_H(\theta_n, \phi_n) \) denote the complex electric field directivity of the antenna element for the \( \theta \) and \( \phi \) components, which are calculated by the method of moments [5]. Here, \( h_{nc} \) represents the equivalent amplitude of the incident waves and can be set to an arbitrary value; thus, it is assumed to have unity amplitude. Further, \( XPR \) is the cross-polarization power ratio [24]. The phases of the vertical \( (\varphi_{Vn}) \) and horizontal \( (\varphi_{Hn}) \) polarization components are independent of each other and uniformly distributed from 0 to \( 2\pi \).

For each path, the two polarization components are combined as a complex sum of vertical and horizontal components as follows:

\[
h_n = h_{Vn} + h_{Hn}
\]  

(3)

The resultant channel response \( h_s \) at the antenna is expressed as the sum of \( N \) paths using the following equation:

\[
h_s = \sum_{n=1}^{N} h_n \exp \left\{ \frac{2\pi d}{\lambda} \cos(\phi_n - \phi_m) \right\} = \sum_{n=1}^{N} h_{nr}
\]  

(4)

where \( \lambda \) is the carrier wavelength in free space, and \( d \) is the distance travelled by the dynamic phantom toward the azimuth direction \( (\phi_m) \).

Therefore, the average power of the reflected waves \( (P_r) \) is obtained by

\[
P_r = \frac{1}{S} \sum_{s=1}^{S} |h_s|^2
\]  

(5)

where \( S \) signifies the number of samples, which means the entire snapshots in a walking motion process.

On the other hand, the channel response of the direct wave can be expressed as

\[
h_d = \sqrt{KP_{Pr}}
\]  

(6)

where \( K \) is defined as the power ratio of the direct \( P_d \) and reflected wave components \( P_r \), usually known as the Rician factor or the K-factor.

As shown in Fig. 3(b), the combined signal response of each path at each arm-swinging angle can be obtained as a vector sum in the following form:

\[
h_{nc} = h_d + h_{nr}
\]  

(7)

Therefore, the overall channel response in a Rice environment is expressed as follows:

\[
h_{sx} = \sum_{n=1}^{N} h_{nc} = \sum_{n=1}^{N} (h_d + h_{nr})
\]  

\[
= \sqrt{KP_r} + \sum_{n=1}^{N} h_n \exp \{ j2\pi f_d \cos(\phi_n - \phi_m) \}
\]  

(8)

where \( f_d = v/\lambda \) is the maximum Doppler frequency, and \( v \) denotes the velocity of the phantom.

Using this model, a Monte Carlo simulation can be carried out when the phantom is moving with the arms swinging, where the K-factor is used as an input variable to represent the relationship between \( P_d \) and \( P_r \) at each arm-swinging angle. The analytical results, presented in Sect. 5, will be compared with the measured results.

Furthermore, the software for controlling the fading emulator is also developed on the basis of the formulations mentioned above. Specifically, time-sequential variations of signals for the surrounding dipole antennas (scatterers) and body-mounted dipole antenna (sensor module), depicted in Fig. 2, can be generated using a combination of Eq. (8), by varying the voltages applied to the phase shifters and attenuators (see Fig. 4), and the calibration method, as discussed in the next section.

4. Calibration Method

Because there is a difference between the indoor radio wave propagation environment and usage scenarios of the fading environment, as shown in Fig. 3(a). Assuming that the \( n \)-th path has a transfer function with vertical and horizontal components, its transfer function at the antenna can be given by

\[
h_{Vn} = \sqrt{\frac{XPR}{1 + XPR}} h_{n} E_V(\theta_n, \phi_n) \exp(j \varphi_{Vn})
\]  

(1)

\[
h_{Hn} = \sqrt{\frac{1}{1 + XPR}} h_{n} E_H(\theta_n, \phi_n) \exp(j \varphi_{Hn})
\]  

(2)

where \( E_V(\theta_n, \phi_n) \) and \( E_H(\theta_n, \phi_n) \) denote the complex electric field directivity of the antenna element for the \( \theta \) and \( \phi \) components, which are calculated by the method of moments [5]. Here, \( h_{nc} \) represents the equivalent amplitude of the incident waves and can be set to an arbitrary value; thus, it is assumed to have unity amplitude. Further, \( XPR \) is the cross-polarization power ratio [24]. The phases of the vertical \( (\varphi_{Vn}) \) and horizontal \( (\varphi_{Hn}) \) polarization components are independent of each other and uniformly distributed from 0 to \( 2\pi \).

For each path, the two polarization components are combined as a complex sum of vertical and horizontal components as follows:

\[
h_n = h_{Vn} + h_{Hn}
\]  

(3)

The resultant channel response \( h_s \) at the antenna is expressed as the sum of \( N \) paths using the following equation:

\[
h_s = \sum_{n=1}^{N} h_n \exp \left\{ \frac{2\pi d}{\lambda} \cos(\phi_n - \phi_m) \right\} = \sum_{n=1}^{N} h_{nr}
\]  

(4)

where \( \lambda \) is the carrier wavelength in free space, and \( d \) is the distance travelled by the dynamic phantom toward the azimuth direction \( (\phi_m) \).

Therefore, the average power of the reflected waves \( (P_r) \) is obtained by

\[
P_r = \frac{1}{S} \sum_{s=1}^{S} |h_s|^2
\]  

(5)

where \( S \) signifies the number of samples, which means the entire snapshots in a walking motion process.

On the other hand, the channel response of the direct wave can be expressed as

\[
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where \( K \) is defined as the power ratio of the direct \( P_d \) and reflected wave components \( P_r \), usually known as the Rician factor or the K-factor.

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Therefore, the overall channel response in a Rice environment is expressed as follows:

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h_{sx} = \sum_{n=1}^{N} h_{nc} = \sum_{n=1}^{N} (h_d + h_{nr})
\]  

\[
= \sqrt{KP_r} + \sum_{n=1}^{N} h_n \exp \{ j2\pi f_d \cos(\phi_n - \phi_m) \}
\]  

(8)

where \( f_d = v/\lambda \) is the maximum Doppler frequency, and \( v \) denotes the velocity of the phantom.

Using this model, a Monte Carlo simulation can be carried out when the phantom is moving with the arms swinging, where the K-factor is used as an input variable to represent the relationship between \( P_d \) and \( P_r \) at each arm-swinging angle. The analytical results, presented in Sect. 5, will be compared with the measured results.

Furthermore, the software for controlling the fading emulator is also developed on the basis of the formulations mentioned above. Specifically, time-sequential variations of signals for the surrounding dipole antennas (scatterers) and body-mounted dipole antenna (sensor module), depicted in Fig. 2, can be generated using a combination of Eq. (8), by varying the voltages applied to the phase shifters and attenuators (see Fig. 4), and the calibration method, as discussed in the next section.

4. Calibration Method

Because there is a difference between the indoor radio wave propagation environment and usage scenarios of the fading
emulator, calibration of the fading emulator is necessary for recreating the actual conditions of the other environments. Therefore, prior to the basic experiment, a procedure for calibrating the fading emulator is described in this section.

Figure 4 shows the circuit of the fading emulator, which is composed of a power combiner, 7 phase shifters, and two attenuators. As can be seen, the power combiner is used to combine the signals from the surrounding dipole antennas with different phases obtained by using the phase shifters, as shown by the red diagram block. Here, ATT1 is used to control the direct wave \( P_d \), and ATT2 is used to control the reflected wave \( P_r \), as mentioned in Sect. 2.

The fading emulator can be calibrated by setting the values of the attenuators, shown in Figs. 2 and 4, using Eqs. (9) and (10) given below.

\[
\begin{align*}
\text{If } & P_d - P_r < K, \text{ then} \\
\text{ATT}1 & (\text{dB}) = 0 \text{ (dB)}, \\
\text{ATT}2 & (\text{dB}) = K (\text{dB}) - E[P_r] (\text{dBm}) \\
\text{If } & P_d - P_r > K, \text{ then} \\
\text{ATT}1 & (\text{dB}) = E[P_d] (\text{dBm}) - E[P_r] (\text{dBm}) - K (\text{dB}), \\
\text{ATT}2 & (\text{dB}) = 0 \text{ (dB)}
\end{align*}
\]

where \( P_d \) and \( P_r \) denote the power of the direct and scattered signals in dBm. Here, \( E[x] \) signifies the expectation or average of the quantity \( x \). The Rician factor or K-factor \( K \), in Eqs. (9) and (10), is defined as the ratio of \( P_d \) to \( P_r \), and it can be measured during the propagation experiment, which will be described later in part C. Moreover, \( P_d \) can be measured with a vector network analyzer (VNA), and \( E[P_r] \) can be measured with the developed fading emulator, shown in Fig. 2, which will be discussed in parts A and B, respectively. With the actual value of the K-factor in a certain situation as a reference, the attenuators in the fading emulator, shown in Fig. 4, can be used to adjust the ratio of \( P_d \) to \( P_r \) to create a realistic radio propagation environment as we require. For example, if \( P_d - P_r \) is less than K-factor as shown in Eq. (9), the signal level of reflected wave will be larger than that in the actual propagation environment.

Thus, we need to set the value of difference into ATT2 to reduce the signal level of reflected wave components to adjust the measured K-factor in the actual propagation experiment. On the contrary, if \( P_d - P_r \) is larger than the actual K-factor as indicated in Eq. (10), it means that the direct wave is so large that the value of difference needs to be set into ATT1 to reduce the signal level of direct wave components to adjust the measured K-factor.

In order to confirm the proposed method of calibration mentioned above, some basic experiments have been carried out using the arm-swinging dynamic phantom. In previous studies [5], [6] the shadowing effects attributed to the arm-swinging motion are shown to simultaneously affect the direct wave between the two on-body antennas and reflected wave components from the surrounding objects. Therefore, it is necessary to measure the direct and multipath signals individually and analyze the relationship between the value of K-factor, \( P_d \) and \( E[P_r] \), to confirm the validity of proposed method of calibration. The measurements are presented in five parts, A, B, C, D, and E, as follows.

A. Measurement of \( P_d \)

Initially, the path loss between the two BAN antennas that represents the power of the direct wave \( P_d \) was measured considering the arm-swinging motion in BAN on-body situation. We chose a half-wavelength dipole antenna as a test antenna because of an easy understanding of the physical mechanism with regard to the measured results owing to simple radiation properties.

In Fig. 5, the picture on the left-hand side shows the photograph of the arm-swinging dynamic phantom [5], and the figure on the right-hand side shows its configuration. The receiving half-wavelength dipole antenna at 950 MHz in the vertical orientation was located at position A on the left-hand side of the waist of the structure. The transmitting antenna was mounted at positions B and C, which are 45° and 135° away from position A in the same horizontal plane around the torso, as shown in the right-hand side fig-
Fig. 6 VSWR vs. angle of the left arm at location A.

Fig. 7 Path loss vs. angle of left arm for different antenna positions.

Fig. 8 Variation of multipath signals vs. angle of the left arm.

ure of Fig. 5. The distances from A to B and A to C around the torso of the phantom can be calculated as 17.3 cm and 51.8 cm, respectively. The separation between the dipole antenna and the surface of the phantom is set to 1 cm. The impedance characteristics when the separation is 1 cm are shown in Fig. 6 for three cases: the results calculated by the method of moments, those measured by the phantom, and the results for a human (22-year-old Japanese male, 70 kg in weight and 175 cm in height). Furthermore, the analytical results when the distance between the antenna and the phantom was 3 cm [5] are also included in Fig. 6. It can be seen that there is little difference between the result of VSWR when the separation is 1 cm and that of 3 cm, which indicates that the separation between the antenna and phantom does not have a serious impact on the impedance characteristics because a dipole antenna with relatively wideband characteristics is used in the experiment. Thus, for a more realistic wearable situation, in this paper, the separation is set to 1 cm in all analyses and measurements.

Additionally, two coaxial cables were used to connect the two dipole antennas to a VNA for measuring the S21 characteristic. Detailed descriptions of the measurement model and procedures are given in [5]. The phantom can swing both the arms to create the shadowing effects. The angle of left arm was changed from −15 to 40 degrees at 5 degrees intervals while the right arm was changed from 40 to −15 degrees simultaneously as the same manner, which has been confirmed by analyzing the statistical measurements of walking motion using the real test persons [6].

Figure 7 shows the measured results with two different positions of the two dipole antennas (A-B and A-C) and the angle of left arm as parameters. As can be seen, when the angle of left arm is varied from −15° to 40°, the curves of path loss change correspondingly for each position. In A-C position, the path loss is greater with considerable variation because of the obstruction of the phantom body and shadowing effects caused by the arm, as shown by the curve with symbol ●. On the other hand, if the two antennas are placed close to each other, in position A-B (shown by the curve with symbol ■), the level of path loss decreases, indicating a strong direct wave level. The characteristics of path loss at these two positions (A-B and A-C) will be used to verify the proposed calibration method, as will be presented later in parts D and E.

B. Measurement of \( P_r \)

The average power of the reflected waves (\( E[P_r] \)) at different angles of the left arm also needs to be measured.

In this case, only the receiving antenna located at position A, shown in Fig. 5, is used for collecting the combined multipath radio waves created by the scattering antennas using the developed RF-controlled fading emulator.

As shown in Fig. 8, when the angle of the left arm is varied from −15° to 40° in intervals of 5°, a significant degradation of approximately 15.5 dB can be observed. The reason is that when the left arm is close to the dipole antenna attached to the waist, the radiation efficiency reduces significantly because of the shadowing effects caused by the arm [5].
To obtain the actual value of the K-factor in indoor on-body Rice channel situations, a preliminary experiment has been conducted using the human phantom with a fixed arm angle. As shown in Fig. 9, an arm-swinging dynamic phantom with salt water inside, which is close to the electrical property of the human body, is used instead of a real test person because of better repeatability [5].

The phantom’s torso has a diameter of 22 cm and a height of 120 cm. The receiving antenna was located at position A shown in Fig. 5 whereas the transmitting antenna was located at positions B and C. The two antennas attached to the phantom were separated by 1 cm from the surface for the experiment. Moreover, the left and right arms were fixed at $-15^\circ$ and $40^\circ$ angles, respectively. For the measurement, the frequency was set to be 950 MHz. The data of the received signals were collected and analyzed on the receiving side.

The left figure of Fig. 10 shows the top view of the indoor measurement environment, which is an $8 \times 6.5$ m classroom at Toyama University. The distance from the floor to ceiling is 3 m. The distance from the human phantom to the wall is set to 1.8 m on the right side and 1 m on the back side. The arms of the human phantom can be fixed at any desired angle, as shown in the right picture of Fig. 10. The phantom was pushed by a person along a distance of 6 m for 20 s with two dipole antennas attached to the phantom.

Figure 11 shows the measured results of the propagation experiment. Figures 11(a) and 11(b) indicate the instantaneous response and cumulative distribution function (CDF) characteristics when the left arm is fixed at $-15^\circ$ and the antennas are mounted at position A-B, shown in Fig. 5. Further, Figs. 11(c) and 11(d) indicate the instantaneous response and CDF characteristics when the left arm is also fixed at $-15^\circ$ and the antennas are mounted at position A-C, shown in Fig. 5. The theoretical curve for Rayleigh response is also included. For each case, measurements have been taken thrice so as to reduce the error of measurement. During the measurement time of 20 s, the number of samples in the receiver was set to be 4000, which means that we recorded data every 0.005 s, as indicated by the horizontal axes in Figs. 11(a) and 11(c). The CDF curves shown in Figs. 11(b) and 11(d) indicate that the measured values of K-factor are 18 dB and 5 dB in the two antenna positions A-B and A-C, respectively.

Moreover, with this propagation experiment, the actual values of K-factor can be measured for different relative antenna positions and different instantaneous angular positions of the arms, which will then be used for the validation of the proposed calibration method in the parts D and E.

**D. Calibration in fading emulator**

After $P_d$ and $E[P_d]$ are analyzed as mentioned above, the K-factor can be achieved on the basis of these two parameters by adjusting the attenuator in the fading emulator. For example, we choose a specific situation when the angle of the left arm is at a reference position of $-15^\circ$. The re-
receivers and transmitters are placed in positions A and B, respectively, as shown in the right figure of Fig. 5. From the propagation experiment described in part C, the K-factor is measured as 18 dB for this case, as indicated by Fig. 11(b). As can be seen in Fig. 7, when the angle of the left arm is $-15^\circ$, the path loss is 25.3 dB shown as Q1. Because the transmission power was set to be 0 dBm, the signal level of the direct wave ($P_d$) is calculated to be $-25.3$ dBm. Moreover, the average reflected wave $E[P_r]$ is $-50.8$ dBm as shown by position Q2 in Fig. 8 when the angle of the left arm is $-15^\circ$. Thus, the difference between $P_d$ and $E[P_r]$, which is equivalent to the K-factor, is 25.5 dB. This value is larger than the actual measured K-factor value of 18 dB. Therefore, Eq. (10) can be selected to calibrate the fading emulator. Using Eq. (10), we set $P_d = 25.3$ dBm and $E[P_r] = 7.5$ dBm. Table 1 shows the estimated K-factors at position A-C.

### Table 1: K-factor estimation for different angles of the left arm with antennas at position A-B.

<table>
<thead>
<tr>
<th>Angle of Left Arm (deg)</th>
<th>$P_d$ (dBm)</th>
<th>$E[P_r]$ (dBm)</th>
<th>$E[P_r]$ (dBm)</th>
<th>$E[P_r]$ (dBm)</th>
<th>K (dB)</th>
<th>18 (Measured by propagation experiment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-15$</td>
<td>$-25.3$ (Q1)</td>
<td>$-32.8$</td>
<td>$-50.8$</td>
<td></td>
<td></td>
<td>25.5</td>
</tr>
<tr>
<td>$-10$</td>
<td>$-26.1$</td>
<td>$-33.6$</td>
<td></td>
<td></td>
<td></td>
<td>25.2</td>
</tr>
<tr>
<td>$0$</td>
<td>$-30.6$ (Q3)</td>
<td>$-38.1$</td>
<td>$-64.3$</td>
<td></td>
<td></td>
<td>26.2</td>
</tr>
<tr>
<td>$5$</td>
<td>$-32.5$</td>
<td>$-40$</td>
<td></td>
<td></td>
<td></td>
<td>25.2</td>
</tr>
<tr>
<td>$10$</td>
<td>$-32.1$</td>
<td>$-39.6$</td>
<td>$-59.3$</td>
<td></td>
<td></td>
<td>19.7</td>
</tr>
<tr>
<td>$15$</td>
<td>$-30.3$</td>
<td>$-37.8$</td>
<td></td>
<td></td>
<td></td>
<td>15.1</td>
</tr>
<tr>
<td>$20$</td>
<td>$-27.9$</td>
<td>$-35.4$</td>
<td></td>
<td></td>
<td></td>
<td>15.9</td>
</tr>
<tr>
<td>$25$</td>
<td>$-25.8$</td>
<td>$-33.3$</td>
<td></td>
<td></td>
<td></td>
<td>17.5</td>
</tr>
<tr>
<td>$30$</td>
<td>$-24.8$</td>
<td>$-32.3$</td>
<td>$-50.1$</td>
<td></td>
<td></td>
<td>17.8</td>
</tr>
<tr>
<td>$35$</td>
<td>$-24.6$</td>
<td>$-32.1$</td>
<td>$-49.7$</td>
<td></td>
<td></td>
<td>17.6</td>
</tr>
<tr>
<td>$40$</td>
<td>$-25.0$</td>
<td>$-32.5$</td>
<td>$-50.3$</td>
<td></td>
<td></td>
<td>17.8</td>
</tr>
</tbody>
</table>

### Table 2: K-factor estimation for different angles of the left arm with antennas at position A-C.

<table>
<thead>
<tr>
<th>Angle of Left Arm (deg)</th>
<th>$P_d$ (dBm)</th>
<th>$E[P_r]$ (dBm)</th>
<th>$E[P_r]$ (dBm)</th>
<th>K (dB)</th>
<th>5 (Measured by propagation experiment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-15$</td>
<td>$-56$ (Q5)</td>
<td>$-64$</td>
<td>$-50.8$</td>
<td>$-4$</td>
<td>7.5</td>
</tr>
<tr>
<td>$-10$</td>
<td>$-56.6$</td>
<td>$-63.9$</td>
<td>$-53.7$</td>
<td></td>
<td>7.3</td>
</tr>
<tr>
<td>$0$</td>
<td>$-60.5$</td>
<td>$-68.5$</td>
<td>$-58.3$</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>$5$</td>
<td>$-68.7$</td>
<td>$-74.5$</td>
<td>$-64.3$</td>
<td></td>
<td>5.8</td>
</tr>
<tr>
<td>$10$</td>
<td>$-79.3$</td>
<td>$-75.4$</td>
<td>$-65.2$</td>
<td></td>
<td>4.1</td>
</tr>
<tr>
<td>$15$</td>
<td>$-94.9$</td>
<td>$-89.5$</td>
<td>$-69.9$</td>
<td></td>
<td>4.5</td>
</tr>
<tr>
<td>$20$</td>
<td>$-111$</td>
<td>$-93.1$</td>
<td>$-72.9$</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>$25$</td>
<td>$-63.8$</td>
<td>$-61.0$</td>
<td>$-50.8$</td>
<td></td>
<td>2.8</td>
</tr>
<tr>
<td>$30$</td>
<td>$-60.3$</td>
<td>$-60.3$</td>
<td>$-50.1$</td>
<td></td>
<td>0</td>
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<tr>
<td>$35$</td>
<td>$-58.8$</td>
<td>$-60.9$</td>
<td>$-49.7$</td>
<td></td>
<td>3.5</td>
</tr>
<tr>
<td>$40$</td>
<td>$-52.7$</td>
<td>$-60.5$</td>
<td>$-50.1$</td>
<td></td>
<td>3.3</td>
</tr>
</tbody>
</table>

E. Verification of the proposed method

After obtaining the values set in the attenuators, the instantaneous K-factors can be estimated for situations where the phantom swings both arms by transforming Eqs. (9) and (10) as follows:

\[
\text{If } P_d - P_r < K, \text{ then} \\
K (\text{dB}) = P_d (\text{dBm}) - [E[P_r] (\text{dBm}) - ATT2 (\text{dB})] \quad (11)
\]

\[
\text{If } P_d - P_r > K, \text{ then} \\
K (\text{dB}) = [P_d (\text{dBm}) - ATT1 (\text{dB})] - E[P_r] (\text{dBm}) \quad (12)
\]

Here, Eq. (12) is selected because we will analyze the same situation mentioned in part D with the left arm at $-15^\circ$ angle and antennas at position A-B. Thus, the K-factors at other angles of the left arm at $5^\circ$ degrees intervals can be estimated using Eq. (12), which are illustrated in Table 1. Thereafter, we conduct the actual experiment, where the human phantom is walking for a distance of 50 wavelengths at 950 MHz, using the fading emulator to confirm the accuracy of the estimated K-factors, shown in the right column of Table 1.

For a certain position, calibrated with the fading emulator, taken as a reference position, as shown in Fig. 12, we only need to change the angle of left arm at $5^\circ$ intervals to measure the combined signal levels of $P_d$ and $E[P_r]$ caused by the fading emulator at every instantaneous angular position. The measured K-factor will be automatically set by the direct wave $P_d$ and reflected waves $E[P_r]$ caused by the movement of the left arm, as shown in Table 1. For example, from position Q3 in Fig. 7 and position Q4 in Fig. 8, we can infer the values of $P_d$ and $E[P_r]$ to be $-30.6$ dBm and $-64.3$ dBm, respectively, when the left arm is at an angle of $0^\circ$. Because ATT1 is set to be 7.5 dB, the K-factor can be calculated as $[(-30.6 \text{ dBm} - 7.5 \text{ dB}) - (-64.3 \text{ dBm})] = 26.2$ dB, as shown in Table 1.

The estimated K-factors at position A-C are also included in Table 2. On the basis of the calibration method at position A-B, we chose the same angle of the left arm at $-15^\circ$ as a reference position. From the propagation experiment described in part C, the K-factor is measured as 5 dB
Fig. 13  CDF variations measured using the fading emulator for different angles of the left arm: (a) position A-B, (b) position A-C.

for this case, as indicated by Fig. 11(d). As can be seen in Fig. 7, when the angle of the left arm is $-15^\circ$, the signal level of the direct wave ($P_d$) is found to be $-56$ dBm, as shown by position Q5, because the transmission power was set to be 0 dBm. The average reflected wave $E[P_r]$ is $-50.8$ dBm as shown by position Q2 in Fig. 8, when the angle of the left arm is $-15^\circ$. Thus, the K-factor can be calculated to be $-5.2$ dB. This value is less than the actual measured K-factor value of 5 dB. Therefore, Eq. (9) is selected to calibrate the fading emulator. Using Eq. (9), the value we set to ATT2 can be calculated as $(5 \text{ dB} - [-56 \text{ dBm} - (-50.8 \text{ dBm})]) = 10.2$ dB, and ATT1 is set to be 0 dB in this case. After the K-factor at the reference position is calibrated, the K-factors at each arm-swinging angle are estimated, as shown in the right column of Table 2. For example, from position Q6 in Fig. 7 and position Q4 in Fig. 8, we can infer the values of $P_d$ and $E[P_r]$ to be $-68.7$ dBm and $-64.3$ dBm, respectively, when the left arm is at an angle of 0°. Because ATT2 is set to be 10.2 dB, using Eq. (11), the K-factor can be calculated as $[(−68.7 \text{ dBm})−(−64.3 \text{ dBm}−10.2 \text{ dB})] = 5.8$ dB, as shown in Table 2.

Figures 13(a) and 13(b) show the CDF variations for four different left arm angles ($-15^\circ$, 0°, 15°, and 40°), when the dipole antennas are located at positions A-B and A-C, respectively. The theoretical curve for Rayleigh response is shown with the solid line. The curves with symbol ◯ indicate the data obtained from the fading emulator whereas the broken lines show the estimated values of K-factor, shown in Tables 1 and 2, which are calculated from the I-zero response. As can be seen, the measured data agree well with the estimated values of K-factor both in positions A-B and A-C, indicating that the method of estimating the K-factor using measured results of $P_d$ and $E[P_r]$ is correct. It can also be seen that when the K-factor is negative, such as the case where the angle of the left arm is 15° as shown in Fig. 13(b), the CDF curve coincides with the Rayleigh distribution. This is attributed to the fact that when the position of two dipole antennas is changed from A-B to A-C, a longer link distance results in an obvious increase of the path loss as shown in Fig. 7, leading to a significant degradation of K-values due to a large reduction of the direct wave compared with the multipath components.

Based on the extensive investigations mentioned above, the proposed method of calibrating the fading emulator is confirmed to be valid. This method can be used for BANOTA testing to realize the actual radio wave propagation scenarios such as for dynamic characteristics attributed to human motion.

5. Experiment When Phantom is Walking

After the proposed calibration method is verified, an experiment to realize the actual Rice channel in the developed fading emulator with continuous human walking motion has been conducted, as presented in this section.

Figure 14 shows the top view of the BAN fading emulator, as introduced in Fig. 2. The dynamic phantom placed at the center is controlled by a computer and can swing both the arms. In addition, 7 scattering half-wavelength sleeve dipole antennas at 950 MHz with radio wave absorbers behind them can create Rayleigh fading signals by varying the phases and amplitudes in the control circuit of the fading emulator. The receiving dipole antenna is fixed at position A, and the transmitting dipole antennas are mounted at positions B and C, as illustrated in this section.

After the K-factor (with values 18 dB and 5 dB), shown in Fig. 11, is calibrated at the reference position where the left arm is at $-15^\circ$, as described in Sect. 4, the experiment can be conducted using the fading emulator for a continuous arm-swinging motion. The left arm was varied from $-15^\circ$ to 40° and back to $-15^\circ$ while the right arm was changed from 40° to $-15^\circ$ and back to 40° simultaneously in the opposite
direction based on the statistical measurements on the actual human walking motion using real test persons [6]. The speed of arm-swing motion is 20 seconds per cycle. On the other hand, the measurement time of the fading emulator is 260 seconds. Therefore, the arms need to swing continuously for 13 cycles to fit the measurement time.

Furthermore, a Monte Carlo simulation based on the proposed analytical Rice channel model, mentioned in Sect. 3, has been carried out. The method of analyzing the combined effects of shadowing-fading is explained in detail in [5], [6]. We simulated the phantom to walk at a stride length of 60 cm. Two strides, equivalent to a two-way swing, are equal to 120 cm, corresponding to 1 cycle of arm-swinging motion. Therefore, during the 13 cycles of arm-swinging motion, the moving distance can be calculated as 1560 cm, which is about 49 wavelengths at 950 MHz. The number of snapshots is set to be 100 samples per wavelength. The XPR is set to be 50 dB, which means that the polarization is assumed to be vertical because only the vertical polarization of the dipole antennas is used in the fading emulator. The values of the initial phases and angle of direction of motion are set the same as those of the actual setup of the fading emulator. The results are analyzed as follows.

Figures 15(a) and 15(c) (shown by the black curve) illustrate the results of instantaneous response measured in the fading emulator for a walking distance of 50 wavelengths at 950 MHz when the dipole antennas are located at positions A-B and A-C, as shown in Fig. 5. Further, Figs. 15(b) and 15(d) (shown by the red curve) illustrate the analytical results using the Monte Carlo simulation.

As can be seen in Figs. 15(a) and 15(b), in situation A-B, the distance between the transmitting and receiving antennas is small, thus $P_f$ is strong enough to enable all the K-factors to be maintained at a high level even after being affected by the shadowing effects caused by arm-swinging motion, as can be inferred in Table 1. However, in situation A-C, shown with Figs. 15(c) and 15(d), because $P_f$ almost disappears, as can be inferred by Fig. 7, the received signal level is mainly contributed by the multipath radio wave components leading to a significant variation of received signals, as shown in the instantaneous response plot.

Figure 16 shows the CDF characteristics of the combined signals when the phantom walks at a stride length of 60 cm during the 13 cycles of arm-swinging motion. The profile with symbol ⊙ shows the measured results obtained from the fading emulator corresponding to Figs. 15(a) and 15(c) whereas the dotted curve with symbol △ indicates the analytical outcome calculated by Monte Carlo simulation corresponding to Figs. 15(b) and 15(d). The theoretical Rayleigh response curve is illustrated with the solid line in the graph.

We can see from Fig. 16 that for both the antenna positions, A-B and A-C, the measured results agree well with the analytical outcome indicating that the Rice channel of BAN on-body situation considering human dynamic characteristics can be realized using the developed fading emulator, which is extremely useful for evaluating actual BAN radio modules in BAN-OTA testing.
6. Conclusion

This paper presents a new methodology for BAN-OTA testing using a developed fading emulator with a dynamic phantom. Providing the fading emulator with an appropriate K-factor that can represent the actual propagation environment indoors is essential. In addition, an implementation of Rice channel to the developed fading emulator in the BAN situation is presented. Then, a method of calibration where the attenuators in the fading emulator are adjusted to achieve the actual K-factor values of the on-body Rice channel is advanced, which is confirmed by analyzing the variation of instantaneous K-factor for each angle of the arm. Finally, an experiment was conducted on the fading emulator when the human phantom is walking with a continuous arm-swinging motion. The results show that using the proposed fading emulator, the actual Rice channel propagation environment considering dynamic characteristics of human walking motion can be realized in BAN-OTA testing.

This study used only vertically polarized dipole antennas because the horizontal polarization dipole antennas of the fading emulator are under construction. For realizing the actual propagation environment indoors, both vertical and horizontal polarization of multipath radio waves should be taken into account when developing the fading emulator. The aim is to realize a BAN-OTA apparatus that can assess the communication quality of commercially available BAN radio modules considering human dynamic characteristics. This will be addressed in future studies and presented in separate papers.

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