Channel Measurement and Modeling Prototype for IEEE 802.22-based Regional Area Networks

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ABSTRACT During the design and development of a reliable transceiver, its performance and robustness are evaluated using channel models that simulate the propagation channel characteristics in a real-world environment. In the case of wide-area communication systems in rural areas such as those based on TV white spaces, long delay multipath fading is one of the dominant factors impairing communication quality, and it is important to apply realistic multipath fading channel models in various application scenarios. Therefore, it is necessary to develop channel measurement and modeling systems that adaptively obtain channel factors and reflect multipath propagation characteristics in various wide-area communication environments. In this study, we developed a flexible channel measurement and modeling prototype applicable to mobile IEEE 802.22-based wide-area communication systems, which can be simply implemented by using programmable hardware and software. The prototype includes a new channel modeling framework that applies an improved double exponential slope model to extract the essential factors of multipath propagation characteristics. To validate the developed prototype, a fading emulator is applied to it to measure the raw data used for modeling. As a result, the multipath fading characteristics measured with the prototype were successfully modeled and reproduced by the proposed channel modeling framework with a high fitness of root mean square delay spread distribution. The derived bit error rate characteristics agreed better with the simulation results compared to the conventional channel model.

INDEX TERMS Channel measurement, channel modeling, IEEE 802.22, prototype, wireless regional area network

I. INTRODUCTION
Future wireless networks will form heterogeneous networks that are highly integrated with Internet of Things (IoT) systems, next-generation intelligent transport systems (ITSs), and advanced cellular systems. Along with the advancement of the wireless networks, the demand for network capacity has also exponentially increased in recent years. According to a forecast [1], global data traffic will increase with a compound annual growth rate of 46% over the next few years. To accommodate data traffic from the increasingly large amount of IoT devices deployed worldwide by wireless communication systems, it is necessary to realize a wide area access network with as large a coverage area as possible.

To support such a wide communication coverage, especially in rural areas, radio communication in television (TV) white spaces (TVWS) has shown great potential [2]. TVWS are temporally and spatially unused TV channels in the very-high frequency (VHF) and ultra-high frequency (UHF) bands. VHF and UHF spectra provide excellent propagation and penetration characteristics, which are suitable for wide-area communication. IEEE 802.22 is a communication system operated in TVWS. It was standardized in June 2011 as a fixed wireless regional area network (WRAN) system supporting a wide coverage range of 10–30 km and line-of-sight (LOS) / non-LOS (NLOS) communication in rural areas with a high effective isotropic radiated power (EIRP) of 4W [3]. Thus, a full-coverage broadband wireless network can be deployed in rural areas at a relatively low infrastructural cost [4]. Wireless devices and receiving technologies incorporating the IEEE 802.22 system have been developed, and their performances have been investigated [5]–[12]. Owing to its excellent propagation properties, the application of IEEE 802.22 in mobile communication is in high demand.
To realize IEEE 802.22-based mobile communication systems for IoT and ITS applications, especially in rural areas, it is necessary to design new receiving algorithms and evaluate their transmission performance. Besides, an appropriate propagation model considering multipath fading in the VHF and UHF bands is crucial for the receiver design and evaluation because propagation models that offer small-scale fading (i.e., multipath fading) are required at the validation stage of link-level simulations. However, to the best of our knowledge, there are few propagation models with a corresponding comprehensive modeling framework that offer practical multipath fading characteristics for UHF wide-area communication systems in rural areas.

For instance, the COST 207 channel model was developed based on the 900 MHz band Global System for Mobile Communication (GSM) and is applicable to urban, rural, and hilly terrain areas [13]. Nevertheless, the model was derived from measured characteristics based on a considerably narrow band system with a bandwidth of 200 kHz or lower [14]; thus, it is not suitable for IEEE 802.22-based systems with a bandwidth of 6 MHz or more.

The WRAN channel model proposed in [15] was derived from measured characteristics based on the Digital Video Broadcasting-Terrestrial system with a bandwidth of 8 MHz. It includes four types of multipath profiles (Profiles A, B, C, and D), and several studies have been carried out on the development of practical receivers with WRAN Profile A [6]–[8]. This channel model simply provides a six-path delay profile where individual excess delay and relative power are defined to each path. However, these delay profiles were developed for fixed long-distance communications with the antenna of the terminal far from the ground; additionally, they are site-specific. Therefore, the WRAN channel models are not suitable for wide-area mobile NLOS environments for IoT and ITS applications [16].

The 3GPP TR 38.901 [17], ITU-R M.2135-1 [18] documents, SUI-6 channel model [19], and ITU-R M.1225 document [20] provide channel models for wide-area mobile communication systems in rural areas. The channel models in [17] and [18] apply a cluster-based single exponential slope model where the arrival of clusters follows a Poisson process. The channel models in [19] and [20] provide three-path and six-path delay profiles, respectively. However, the operation band of the IEEE 802.22 system is not completely covered in the 3GPP TR 38.901 channel model, SUI-6 channel model, and the ITU-R M.1225 document. Furthermore, the user terminal speed is not clarified for rural macro-cell scenarios in these models. In addition, for channel models in [17] and [18], the channel coefficient generation framework for mobile communications and validation of the propagation characteristics reproducibility are not fully clarified. Therefore, their flexibility and adaptivity are limited from IEEE 802.22 diverse usage scenarios.

To derive propagation models that can be applied for various IoT and ITS user cases in IEEE 802.22-based mobile communication systems, field experiments assuming the applications scenario are essential. [21]–[25] have performed measurements of propagation characteristics and showed the statistical characteristics of the root mean square (RMS) delay spread, delay profile, and spectrum spread. However, there are no appropriate methods to reproduce the channel characteristics in simulations.

Regarding the channel modeling framework, Ohara et al. [16] provides a WRAN channel modeling scheme for various applications in a mobile NLOS urban environment in the VHF band. Similar to [17] and [18], an exponential power decay structure and a Poisson process were applied for the modeling. A Saleh-Valenzuela (S-V) model-based multi-cluster stochastic channel model was applied to the model from measured delay profiles [26]. [16] measured channel characteristics with an orthogonal frequency division multiplexing (OFDM)-based signal in the VHF band with NLOS environment and showed that the received channel impulse responses (CIRs) follow the generalized extreme value (GEV) distribution. Then, [16] also proposed a method to extract channel factors, called multipath components (MPCs), that characterize the S-V model. This modeling scheme is widely applicable if CIRs are measured with mobile urban NLOS communications in the VHF band. However, the actual multipath clustering algorithm and channel coefficient reproduction framework are incomplete. Thus, the feasibility of the concept in [16] is insufficient for the IEEE 802.22 system targeted in this study. Furthermore, owing to the different propagation characteristics in rural areas, the generated channel coefficient is not compatible with the IEEE 802.22 system in the UHF band.

To cope with various application scenarios of near-future IEEE 802.22-based IoT and ITS networks in rural areas, an adjustable channel model reflecting a realistic propagation environment is essential. Due to the limitations of the existing channel models, it is necessary to develop a flexible channel measurement and modeling prototype.

In this study, we developed a comprehensive channel measurement and modeling prototype for IEEE 802.22-based regional area networks. For prototype development, the IEEE 802.22 signal is generated and transmitted by a programmable signal generator (SG). Then, the signal propagates through various environments according to the application scenario. The propagated signal is received and digitalized by a flexible software defined radio (SDR)-based receiver. Ultimately, the desired signal is extracted and modeled by applying the proposed channel modeling framework. Because the channel modeling scheme in [16] is deficient, an improved statistical multi-cluster double exponential decay channel modeling algorithm is proposed in this study for the IEEE 802.22 communication system under a mobile NLOS rural environment in the UHF band for IoT and ITS applications. Furthermore, we apply a
dynamic GEV parameter according to the arrival time of clusters. In addition, we propose a framework to reproduce channel coefficients allowing flexible link-level simulations. For validation, a set of measurement experiments are performed using the developed prototype, and a set of delay profiles are measured by receiving the IEEE 802.22-based transmission signals through a hardware fading emulator (FE). Then, the parameters are extracted using the proposed algorithm, and the reproduced channel model is compared with the raw measurement channel data. Moreover, the bit error rate (BER) of IEEE 802.22 is evaluated by using the channel models based on the extracted parameters and raw measurement channel data. It is confirmed that the propagation channel measured with the prototype can be modeled and reproduced with excellent fit in statistical characteristics.

The main contributions of this paper can be summarized as follows:

- An IEEE 802.22-based channel measurement and modeling prototype with a modified channel modeling framework is developed for future IEEE 802.22-based mobile communication systems in rural areas. The prototype can be simply implemented by using programmable hardware and software.
- A new S-V model-based channel modeling algorithm applicable to the developed prototype is proposed.
- The developed prototype is experimentally validated under three different long delay multipath fading conditions.

The rest of this paper is organized as follows. In Section II, general specifications of IEEE 802.22, the proposed channel measurement and modeling prototype, and the S-V model are described. In Section III, the conventional channel modeling scheme in [16] is explained. In Section IV, a proposed channel modeling algorithm and channel reproduction framework are described. The performance of the proposed channel measurement and modeling prototype is evaluated in Section V. Finally, the paper is concluded in Section VI.

II. OVERVIEW OF THE IEEE 802.22-BASED CHANNEL MEASUREMENT AND MODELING PROTOTYPE

A. IEEE 802.22 SYSTEM

IEEE 802.22 [3] was standardized as the first WRAN supporting unlicensed operation in the TV broadcast band. IEEE 802.22 is basically a point-to-multipoint fixed communication system based on orthogonal frequency division multiple access with time division duplex (OFDMA / TDD) and is commonly used in rural areas. Table I presents the system parameters defined in IEEE 802.22. Channel bandwidths of 6, 7, and 8 MHz are supported to allow use in various countries and regions worldwide. The physical layer parameters are designed to enable a transmission distance of up to 30 km, and the coverage can be expanded to 100 km with appropriate scheduling at the base station (BS).

In the frequency domain, 60 subchannels, each of which consists of 28 subcarriers, are assigned to the frame. In the time domain, the IEEE 802.22 frame is composed of 26–41 OFDM symbols according to the cyclic prefix length and bandwidth and is divided into down- and up-stream subframes. A transmit/receive transition gap of 210 µs is allocated between the down- and up-stream subframes to ensure a specific transition time from down- to up-stream sequence at the customer premises equipment (CPE). Here, 10 µs is reserved for physical transition time from reception to transmission, and the remaining 200 µs absorbs transmission time with a long-distance of up to 30 km. Owing to its excellent communication coverage, IEEE 802.22 is expected to be utilized as a cost-effective and wide coverage communication system in rural areas, where the users are sparsely located.

B. CHANNEL MEASUREMENT AND MODELING PROTOTYPE FRAMEWORK

Channel measurement and channel state estimation technologies used for wireless communication system have been investigated in [27] and [28]. However, the framework for multipath fading channel modeling is not clarified in these works. In this study, we propose a channel measurement and modeling prototype framework applicable to IEEE 802.22-based mobile communication systems as shown in Fig. 1. The prototype is composed of a signal transmitter, signal receiver, and signal processor with a channel modeling module.

In this prototype, a radio frequency (RF) signal generator (SG) is employed as a signal transmitter due to its simple configuration and implementation for various waveforms and operation bands. The digital baseband signal is generated by inserting the reference data known in advance by following the IEEE 802.22 standard PHY frame structure; this process can be accomplished using software tools. Afterwards, the

| Item                        | Specification          |
|-----------------------------|------------------------|
| Frequency range             | 54 – 862 MHz           |
| Channel bandwidth           | 6, 7, or 8 MHz         |
| Data rate                   | 4.54 – 22.69 Mbit/s    |
| Transmit EIRP               | 4W maximum             |
| Multiple access / duplex    | OFDMA / TDD            |
| FFT size                    | 2,048                  |
| Cyclic prefix (CP) length   | 1/4, 1/8, 1/16, 1/32   |

FIGURE 1. Framework of the proposed channel measurement and modeling prototype.
baseband signal is input into the SG and converted to an RF signal. The RF signal is received and processed by applying an SDR-based device, enabling flexible RF parameter re-programming, simple outdoor / indoor operation, and offline baseband signal processing. The received RF signal is down-converted and sampled into a baseband digital signal with an analog-to-digital converter (ADC). Then, the digital signal is recorded in the embedded storage. As the channel modeling module input, the signal including the reference data is extracted from the recorded signal for the following channel modeling process. In the channel modeling module, a proposed channel modeling algorithm is applied, and the essential factors of the multipath propagation channel are extracted by implementing the proposed algorithm. Similar to [16], an S-V model-based channel modeling algorithm is developed.

C. S-V CHANNEL MODEL

Fig. 2 shows a schematic of an S-V channel, which is widely used to describe propagation characteristics in NLOS communication systems as a double exponential delay model with MPCs [26]. The CIR of the S-V model is expressed as

$$h_{SV} (\tau) = \sum_{k=1}^{K} \sum_{l=1}^{L_k} g_{k,l}(\tau)e^{j\varphi_{k,l}} \delta (\tau - \tau_k - \tau_{k,l}),$$  

where $k$ and $l$ denote the cluster index and the ray index in the $k$-th cluster, respectively; $K$ and $L_k$ denote the total number of clusters and rays in the $k$-th cluster, respectively; $g_{k,l}$ and $\varphi_{k,l}$ are the amplitude and phase of the ray, respectively; $\tau_k$ and $\tau_{k,l}$ are the arrival time of the $k$-th cluster and the $l$-th ray in the $k$-th cluster, respectively; and $\delta (\cdot)$ is the Dirac delta function. The arrival of each cluster and ray follows a Poisson process. Thus, the probability density of the cluster and ray arrival times can be expressed as follows:

$$p(T_k|T_{k-1}) = \lambda e^{-\lambda(T_k-T_{k-1})}, \quad k > 1,$$  

$$p(\tau_{k,l}|\tau_{k,l-1}) = \lambda e^{-\lambda(\tau_{k,l}-\tau_{k,l-1})}, \quad l > 1,$$  

where $\lambda$ and $\lambda'$ denote the average arrival rate of clusters and rays, respectively. The average power of the ray in the S-V model is attenuated exponentially with the arrival time. The average path power gain of the $l$-th ray in the $k$-th cluster, except for the first ray in the first cluster, is given by

$$E[g_{k,l}^2] = E[g_{1,1}^2] e^{-\gamma T_k} e^{-\gamma \tau_{k,l}},$$  

where $\Gamma$ and $\gamma$ denote the power decay factors of the cluster and ray, respectively. The ray amplitude gain fluctuation distribution $\sqrt{g_{k,l}^2 / E[g_{k,l}^2]}$ agrees well with the log-normal distribution in the S-V model. In previous studies, the GEV distribution [29] fitted the ray amplitude gain distribution fluctuation better than a log-normal distribution [16], [30], [31] because the GEV distribution is a flexible integrated distribution. The cumulative distribution function (CDF) of the log-normal distribution is defined as

$$P_{\log-norm}(s) = \frac{1}{\sigma \sqrt{2\pi}} \int_{-\infty}^{\frac{(\ln s - \mu)^2}{2\sigma^2}} e^{-\frac{1}{2}} \, \mathrm{d}r,$$  

where $\mu$ and $\sigma$ are the expected value and standard deviation, respectively. The CDF of the GEV distribution in the case of $1+\xi (s-\mu')/\sigma' > 0$ is defined as

$$P_{GEV}(s) = \begin{cases} e^{-\xi (s-\mu')/\sigma'}, & \xi \neq 0, \\ 0, & \xi = 0 \end{cases}$$  

where $\mu'$, $\sigma'$, and $\xi$ are the location, scale, and shape parameters, respectively. These parameters are extracted from the measurement data as the channel factors of multipath propagation characteristics, as shown in Table II.

III. CONVENTIONAL CHANNEL MODELING FRAMEWORK

In [16], a channel modeling scheme for a 200-MHz broadband mobile communication system is developed based on the S-V model. Instead of the log-normal function applied in the conventional S-V model, a GEV distribution function is applied to the power fluctuation fit. For this channel modeling framework, unique channel factors are applied to all clusters.

Before applying the channel modeling scheme, the reference signal including the data known in advance used for channel propagation characterization and the measured signal including the raw data propagated through the multipath channel are collected. Then, the CIR is calculated as follows [32]:

$$h_{me}[p] = \frac{1}{N} \sum_{n=1}^{N} s_{me}[n] s_{re}^*[n - p],$$  

$$h_{re}[p] = \frac{1}{N} \sum_{n=1}^{N} s_{re}[n] s_{re}^*[n - p],$$

where $h_{me}$ and $h_{re}$ are the measured and reference CIRs, respectively; $s_{me}$ and $s_{re}$ are the measured and reference signals.

![FIGURE 2. Schematic of a Saleh-Valenzuela channel.](image)

| Parameter       | Description                  |
|-----------------|------------------------------|
| $\Gamma$ [dB/s] | Cluster power-decay factor   |
| $\gamma$ [dB/s] | Ray power-decay factor       |
| $1/\Lambda$ [s] | Average cluster arrival interval |
| $1/\lambda$ [s] | Average ray arrival interval  |
| $\mu'$         | GEV location parameter       |
| $\sigma'$      | GEV scale parameter         |
| $\xi$          | GEV shape parameter         |
respectively; \( N \) is the discrete time length of the measured signal; \( n \) and \( p \) are the sample indices of the measured signal and the excess delay, respectively; and \( (\cdot)^* \) denotes the complex conjugate.

In general, the framework of this scheme can be divided into several blocks: MPCs extraction, MPCs clustering, and channel factors extraction. First, the MPCs are extracted from the raw data obtained from measurements by applying the successive interference cancellation (SIC) algorithm shown in Algorithm 1 [33].

Algorithm 1: Simplified SIC Algorithm

Input: \( h_{re} \) and \( h_{me} \)

Output: \( M, p, \beta, \phi, \) and \( \phi \)

1: Initialize the path index \( m = 1 \)
2: Initialize the SIC CIR as \( h_{SIC}[p] = h_{me}[p] \)
3: \textbf{do while} \( 20 \log_{10}(\max(|h_{SIC}^{m-1}[p]|)/\max(|h_{me}[p]|)) > P_{th} \)
4: Extract the excess delay sample of the \( m \)-th path as \( p_m = \arg \max_{\mathcal{P}} |h_{SIC}^{m-1}[p]| \)
5: Extract the amplitude of the \( m \)-th path as \( \beta_m = |h_{SIC}^{m-1}[p_m]| \)
6: Extract the phase of the \( m \)-th path as \( \phi_m = \angle h_{SIC}^{m-1}[p_m] \)
7: Generate the replica of CIR from the \( m \)-th path as \( h_{rep}^{m}[p] = \beta_m e^{i\phi_m} h_{re}[p - p_m] \)
8: Update the SIC CIR as \( h_{SIC}^{m}[p] = h_{SIC}^{m-1}[p] - h_{rep}^{m}[p] \)
9: Set \( \mathbf{p}[m] = p_m \)
10: Set \( \beta[m] = \beta_m \)
11: Set \( \phi[m] = \phi_m \)
12: Update the path index as \( m = m+1 \)
13: \textbf{end}
14: Set \( M = m-1 \)
15: \textbf{return} \( M, \beta, \phi, \) and \( \phi \)

In Algorithm 1, \( P_{th} \) indicates the threshold of the SIC CIR, which was set to \(-20 \) dB according to [16]; \( M \) indicates the number of extracted MPCs; and \( \beta, \phi, \) and \( \phi \) indicate the excess delay, amplitude, and phase arrays, respectively.

Subsequently, the MPCs are clustered by applying a K-power-means algorithm, as shown in Algorithm 2 [34]. In Algorithm 2, \( \mathbf{c} = [c_1, c_2, \cdots, c_K] \) and \( K \) represent the centroids of clusters after \( i \) times iterations and the number of clusters, respectively; \( \sigma_{std} \) represents the standard deviation of the excess delay array \( \mathbf{p} \); \( R_k[m] \) indicates the optimal index of the cluster which the \( m \)-th element in \( \mathbf{p} \) belongs to. Besides, \( \mathcal{M}(m, k) \) and \( \mathbf{c} \) represent the MCD between excess delay of the \( m \)-th path and the \( k \)-th centroid of clusters in the \( i \)-th iteration and the final cluster centroid after the application of the clustering algorithm, respectively. Here, the number of clusters is determined by visual inspection as shown in [16]. Afterwards, the channel factors are extracted by applying the regression functions described in Section II.

Algorithm 2: K-power-means Algorithm

Input: \( p, \mathbf{c}, \) and \( K \)

Output: \( R_k \) and \( \mathbf{c} \)

1: Initialize the iteration index \( i = 1 \)
2: \textbf{do while} \( \mathbf{c} \neq \mathbf{c}^{-1} \)
3: Calculate the multipath component distance (MCD) of all MPCs as follows:

\[
\mathcal{M}(m, k) = \frac{|p_m - c_k^{-1}|}{\sigma_{std}} \cdot \frac{\max}{\max}
\]

(15)

\[
\Delta p_{max} = \max\{|p_m - c_k^{-1}|\}
\]

(16)

4: Calculate the index of cluster for each MPC \( R_k[m] \) as follows:

\[
R_k[m] = \arg \min_k \{\mathcal{M}(m, k)\}
\]

(17)

5: Update the cluster centroid as follows:

\[
c_k^{i} = \frac{1}{\sum_{k[m]=k} p_m} \sum_{k[m]=k} p_m
\]

(18)

6: Update the iteration index \( i = i + 1 \)
7: \textbf{end}
8: Set \( \mathbf{c}^{i} = \mathbf{c}^{-1} \)
9: \textbf{return} \( R_k \) and \( \mathbf{c} \)

By applying this channel modeling scheme, the propagation characteristics of a 200-MHz broadband mobile system is clarified. However, there are several deficiencies when applying this channel modeling scheme to the proposed IEEE 802.22-based channel measurement and modeling prototype. First, a K-power-means algorithm is applied in this modeling scheme, while the method to decide the optimal number of clusters and the initial centroids of clusters are not clarified. This deficiency causes the difficulty in the implementation for various application scenarios. Second, the channel reproduction framework is not clarified, resulting in an obstacle for researchers to validate the channel modeling framework and evaluate the performance of the receiving algorithm. Furthermore, due to the geographical differences between urban and rural areas, the performance of the power fluctuation function in this modeling scheme is not sufficient for the IEEE 802.22-based channel measurement and modeling prototype. Therefore, an improved channel modeling framework is required for our proposed prototype.

IV. PROPOSED CHANNEL MODELING FRAMEWORK

Fig. 3 shows a flowchart of the proposed channel modeling framework, which can be broadly divided into four parts: data collection, data processing, modeling, and channel coefficient reproduction. Compared with the conventional channel modeling framework, an improved K-power-means algorithm
is proposed. Here, the framework for channel coefficient reproduction is clarified.

### A. DATA COLLECTION

For the data collection, the reference signal used for propagation channel characterization is transmitted by the signal transmitter module of the proposed channel measurement and modeling prototype through the RF cable and recorded by the signal receiver as $s_{rec}$. To collect the measured signal, the reference signal is transmitted through the propagation channel and recorded by the signal receiver. Then, raw digital in-phase and quadrature signals with reference signal information are extracted as measured signal $s_{meas}$.

### B. DATA PROCESSING

Similar to the conventional channel modeling framework described in Section III, the data processing stage is composed of CIR calculation, MPC extraction, and MPC clustering. The reference and measured CIRs are calculated using (7) and (8). The MPCs are extracted from the measurement CIR by applying Algorithm 1. It is worth noting that $P_b$ is set to $-40$ dB according to [15] due to different propagation environments. Afterwards, an improved $K$-power-means clustering algorithm is applied to MPC clustering. Instead of the fuzzy scheme in the conventional channel modeling framework described in Section III, a simplified cluster validity algorithm [35] and a max-min algorithm [36] are applied for optimizing the number of clusters and the initial centroids of clusters, as shown in Algorithm 3 and 4, respectively.

In Algorithm 3, $X_k$ represents the indices of the MPCs that belong to the $k$-th cluster, and $K_{opt}$ represents the optimal number of clusters. In this study, the variable $K_{min}$ is set to 2 considering the limitations of the $K$-power-means algorithm, and $K_{max}$ is set to 12 based on previous studies [17], [37].

After deciding the optimal number of clusters and the initial centroids of clusters, the conventional $K$-power-means algorithm in Algorithm 2 is performed.

#### Algorithm 3: Cluster Validity Algorithm

**Input:** $p$, $b$, $K_{min}$, and $K_{max}$

**Output:** $K_{opt}$

1: \[ \text{do for all number of clusters } K = K_{min} \text{ to } K_{max} \]
2: \[ \text{Calculate initial centroid } c_0 \text{ by applying the } \]
3: \[ \text{Max-Min algorithm expressed in Algorithm 4} \]
4: \[ \text{Cluster } p \text{ with the } K \text{-power-means } \]
5: \[ \text{algorithm as } \]
6: \[ \{R_c, c\} = \text{KPowerMeans(} p, c_0, K \text{)} \]
7: \[ \text{Calculate the intra-cluster distance as } \]
8: \[ d_{\text{intra}} = \frac{1}{M} \sum_{k=1}^{K} \sum_{m \in X_k} |p[m] - c_k|^2 \] (19)

#### Algorithm 4: Max-Min Algorithm

**Input:** $p$, $K$

**Output:** $c^0$

1: \[ \text{Initialize the first cluster centroid as } \]
2: \[ c_0^0[1] = \min p \]
3: \[ \text{for } k = 2 \text{ to } K \]
4: \[ \text{do } \]
5: \[ \text{Calculate the distances between } \]
6: \[ d[m] = \min \{p[m] - c_i^0 \} \]
7: \[ \text{end } \]
8: \[ \text{Set } c_0^k[k] = p[m_k] \]
9: \[ \text{Set } c_k = \{c_0^0[1], c_0^0[2], ..., c_0^0[k] \} \]
10: \[ \text{end } \]
11: \[ \text{return } c_0^0 \]

#### C. MODELING

The MPC parameters are extracted in the cluster modeling process. The essential parameters are the power decay factor, path arrival rate, and the statistical parameters of path power gain fluctuations, as shown in Table II.

The power decay factor indicates the power decay rate with the arrival time of each cluster or ray. In the S-V model, the average power of the cluster and each ray within a cluster is attenuated exponentially with the arrival time. In this study, the cluster power indicates the power of the strongest ray in each cluster. The ray power in the $k$-th cluster is normalized by the $k$-th cluster power. Thus, the power decay factor of the $k$-th cluster and rays in the $k$-th cluster can be linearly regressed as follows:

\[ \ln \left( \frac{E[\beta_{k,i}]}{E[\beta_{k,1}]} \right) = -\frac{r p_{k,i}}{R_s}, \] (23)

\[ \ln \left( \frac{E[\beta_{k,i}]}{E[\beta_{k,1}]} \right) = -\frac{r (p_{k,i} - p_{k,1})}{R_s}, \] (24)
where $E[\beta_k]$ and $E[\beta_k^2]$ are the cluster power of the $k$-th cluster and the ray power of the $l$-th ray in the $k$-th cluster, respectively; $p_k$ and $p_k^*$ indicate the excess delay sample of the $k$-th cluster and the $l$-th ray in the $k$-th cluster, respectively; $F_s$ is the sampling rate of the used communication system (i.e., $F_s = 6.856$ MHz according to [3]); and $\Gamma$ and $\gamma$ are the power decay factors of the cluster and ray in each cluster, respectively.

The arrival rate of the cluster and ray can be linearly regressed by the CDF arrival interval between clusters and rays. According to (2) and (3), the relationship between the follow:

$$\ln(1 - D(p_k|p_{k-1})) = -\Lambda(p_k - p_{k-1})/F_s,$$  \hspace{20pt} (25)

$$\ln(1 - D(p_{k,l}|p_{k,l-1})) = -\lambda (p_{k,l} - p_{k,l-1})/F_s,$$  \hspace{20pt} (26)

where $D(x|y)$ is a CDF of the arrival interval between $x$ and $y$. In this study, the regression of the path power gain fluctuations was converted into the regression of the path amplitude gain fluctuations. The path amplitude gain was fitted with a dynamic GEV distribution instead of the conventional log-normal or GEV distributions. For the dynamic GEV distribution fitness process, the location, scale, and shape parameters were estimated individually for each cluster [38]. Note that the GEV parameters are estimated using maximum likelihood method in this study. Compared with the conventional GEV distribution, different GEV parameters were applied to individual arrival clusters considering the different obstacle characteristics. Ultimately, $K$ sets of the GEV distribution parameters $\mu_k$, $\sigma_k$, and $\xi_k$ were derived, where $k$ is the cluster index.

### D. CHANNEL COEFFICIENT REPRODUCTION

In a wide area and mobile environment, fading is caused by the MPCs composed of delayed waves with different arrival times due to faraway obstacles as well as the Doppler spectrum spread due to the surrounding obstacles. Therefore, a joint S-V-Jakes model is proposed and applied to channel coefficient reproduction in this study. The conventional Jakes model provides a Rayleigh fading channel that generates a Doppler spectrum by synthesizing the arrival rays in uniform directions, which are reflected by nearby obstacles and have a similar delay spread [39]. The proposed S-V model provides a frequency-selective fading channel that generates multipath propagation by synthesizing the arrival paths, which are reflected by faraway obstacles and have a different delay spread.

The proposed joint S-V-Jakes model combines the delay spread and spectrum spread features of the Jakes and S-V models. The complex fading fluctuation factors of the S-V-Jakes model can be calculated as a proportional superposition of the Jakes-model fading factors for each path in the S-V model as follows:

$$h(t) = \frac{1}{\sqrt{\pi \beta_k^2}} \sum_{k=1}^{K} \beta_k h_k^t(t - \tau_k) + j\beta_k h_k^Q(t - \tau_k),$$  \hspace{20pt} (27)

where $K = 6$ is the number of multipaths in the S-V model; $k$ is the multipath index; $\tau_k$ is the delay spread of the $k$-th path in the S-V model; and $h_k^t$ and $h_k^Q$ are the in-phase and quadrature Jakes model-based fading components, respectively. Jakes model-based fading components can be calculated as follows [39]:

$$h_k^t(t) = \frac{1}{\sqrt{N_1+1}} \sum_{n=1}^{N_1} \frac{\cos(n\pi t X)}{\cos(2\pi f_0 t \cos(n\pi t X))} + \frac{\cos(2\pi f_0 t)}{\sqrt{N_1+1}} t,$$  \hspace{20pt} (28)

$$h_k^Q(t) = \frac{2}{\sqrt{N_1}} \sum_{n=1}^{N_1} \frac{\cos(n\pi t X)}{\cos(2\pi f_0 t \cos(n\pi t X))} + \frac{\cos(2\pi f_0 t)}{\sqrt{N_1}} t,$$  \hspace{20pt} (29)

where $f_0$ is the maximum Doppler frequency; $N = 4N_1 + 2$ is the number of rays from uniform directions in the Jakes model; and $n$ is the ray index. In this study, $N_1$ was set to 6 according to [40]. By applying the joint S-V-Jakes model, a time- and frequency-selective fading channel can be reproduced to simulate the propagation environment in wide-area mobile communication. We developed a channel reproduction framework based on the proposed joint S-V-Jakes model to generate channel coefficients with the channel modeling parameters. Fig. 4 shows the proposed channel reproduction framework flowchart.
V. PERFORMANCE EVALUATION

In this section, the validation results for the developed channel measurement and modeling prototype are presented. For a convenient and flexible validation, an off-the-shelf FE device is used to emulate the actual radio propagation environment by setting channel delay profiles. Subsequently, the conventional and proposed channel modeling frameworks described in Sections III and IV, respectively, were applied to the prototype, and the channel factors were extracted. Finally, the channel coefficients were reproduced, and the evaluation results were compared.

A. EXPERIMENTAL SETUP

Fig. 5 shows a block diagram of the experimental setup used in this study, and Table III presents the specifications of the experimental equipment [38], [41]. In the validation experiment, the IEEE 802.22 signal generated by a signal transmitter based on an SG was measured with an SDR-based signal receiver through the FE. A multipath FE (NJZ-1600D) was used to emulate the propagation channel. The FE could emulate the fading channel for RF band signal with broadband of up to 20 MHz. A delay profile with up to 12 paths was supported, and Rayleigh and Rice distribution-based fadings were independently applied to each path. For the validation, delay profiles of the WRAN channel model with six paths were applied to the FE as in [15]. Rayleigh distribution-based fading was applied to each path for emulating the NLOS environment, as shown in Fig. 6. Four delay profiles, referred to as Profiles A, B, C, and D, are generally defined as the WRAN channel model; however, Profile D is not used in this study owing to its fuzzy delay profile. For the measured signal $s_{me}$ collection, the transmitted RF signal propagates through the FE and is received by the SDR-based signal receiver. For each delay profile, a 30-s $s_{me}$ was recorded at the receiver; one set of measured signals was collected for each of Profiles A, B, and C. The excess delay and relative amplitude of Profiles A, B, and C are summarized in Table IV. The velocity of the user terminal was set to 80 km/h to imitate the communication scenario for highly mobile vehicles and maintain the Rayleigh characteristics of fading pitches generated by the FE. For the reference signal $s_{re}$ collection, the transmitted RF signal is directly recorded by the SDR-based receiver. Details of the system parameters are given in Table V.

B. CHANNEL FACTOR EXTRACTION

After obtaining $s_{me}$ and $s_{re}$, the measured and reference CIRs were derived using (7) and (8), and the SIC-based MPC extraction process was performed in the personal computer (PC)-based signal processor. Then, the extracted MPCs were clustered by applying the improved K-power-means algorithm described in Section IV. Based on the results of the intra- and inter-cluster distance ratios obtained with Algorithm 3, $K = 6$ was set as the optimal number of clusters for Profiles A, B, and C, as shown in Fig. 7. Then, Algorithm 2 was applied to perform the clustering with the initial cluster centroids obtained by Algorithm 4. Fig. 8 shows an example of the clustering result of the extracted paths obtained for Profile A. Fig. 9 shows the linear regression results of the arrival rate of clusters and rays. Because the estimated average ray arrival rate in each cluster is larger than the sampling rate of the IEEE 802.22 system, only one ray is included per cluster. Thus, the ray power decay factor and ray amplitude gain fluctuation are not considered in the following analysis, and six MPCs are considered during the modeling process according to the measurement result. Fig. 10 shows the fitting results of the cluster power decay factor, and Table VI summarizes the estimated cluster arrival rate and cluster power decay factor for Profiles A, B, and C. Table VI also presents the model parameters obtained by fitting the conventional GEV and proposed dynamic GEV distributions described in Sections III and IV, respectively.
C. EVALUATION RESULTS

After obtaining the channel factors with the channel modeling frameworks described in Sections III and IV, the framework described in Section IV is applied to reproduce the channel coefficients. First, the initial average power and arrival time of the first path are 0 dB and 0 µs, respectively. The arrival interval, which follows an exponential distribution with the estimated arrival rate $\lambda$, is generated for each arrival path. Here, according to the measurement results, the path arrival interval for the reproduction of Profiles A, B, and C is 2.0–8.0, 1.5–4.6, and 1.6–16 µs, respectively, as 99.9% of the arrival time is within this range. With the arrival interval between paths, the arrival time of each path $\tau_k$ can be calculated. According to the arrival time of each path and the estimated path power decay factor $G$, the average power of each path can be calculated. Then, the power fluctuation factor of the $k$-th path is also generated according to the arrival time as follows:

$$d = \arg\min_d \{|\tau_k - \tau_k^d|\}, \quad (30)$$

where $d$ is the cluster index and $\tau_k^d$ is the centroid of the $K$-th path.
power-means clustering result. For the conventional channel modeling framework described in Section III, GEV parameters $\mu', \sigma', \text{and} \xi$ are applied uniformly to all paths. For the proposed channel modeling framework, the corresponding GEV parameters $\mu_j^k, \sigma_j^k$, and $\xi_j^k$ were chosen as the power fluctuation factors of the $k$-th path. To avoid large power fluctuations between paths, the power difference between the adjacent paths for the reproduction of Profiles A, B, and C is controlled within 15, 25, and 30 dB, respectively, according to the measurement results. The relative power of each path is calculated as the product of the average power and the power fluctuation value, as explained in Section II. Finally, with the excess delay and the relative power of each path generated with the proposed channel modeling framework, the multipath fading is determined as the proportional superposition of the fading factors generated by applying the Jakes model of each arrival path. To validate

### FIGURE 9. Fitting result of cluster and ray arrival rate.

(a) Profile A.  
(b) Profile B.  
(c) Profile C.

### FIGURE 10. Fitting result of cluster power decay factor.

(a) Profile A.  
(b) Profile B.  
(c) Profile C.

### TABLE VI

EXTRACTED CHANNEL FACTOR OF EXPERIMENTAL MEASUREMENT

| Parameter | Profile A | Profile B | Profile C |
|-----------|-----------|-----------|-----------|
| $1/\Lambda [s]$ | $1/\Lambda [s]$ | $\Gamma [\text{dB/s}]$ | $1/\Lambda [s]$ | $1/\Lambda [s]$ | $\Gamma [\text{dB/s}]$ | $1/\Lambda [s]$ | $1/\Lambda [s]$ | $\Gamma [\text{dB/s}]$ |
| $1.97\times10^6$ | $1.53\times10^8$ | $1.82\times10^6$ | $1.08\times10^6$ | $3.80\times10^4$ | $2.35\times10^6$ | $3.16\times10^6$ | $3.40\times10^4$ | $9.60\times10^5$ |
| $\mu'$ | $\sigma'$ | $\xi$ | $\mu'$ | $\sigma'$ | $\xi$ | $\mu'$ | $\sigma'$ | $\xi$ |
| 0.37 | 0.32 | 0.72 | 0.49 | 0.44 | 0.51 | 0.27 | 0.29 | 0.93 |
| Path index | $\mu_k'$ | $\sigma_k'$ | $\xi_k$ | $\mu_k'$ | $\sigma_k'$ | $\xi_k$ | $\mu_k'$ | $\sigma_k'$ | $\xi_k$ |
| $k = 1$ | 0.34 | 0.22 | -0.10 | 0.19 | 0.11 | -0.08 | 0.12 | 0.07 | -0.05 |
| $k = 2$ | 0.26 | 0.15 | -0.06 | 0.84 | 0.52 | -0.09 | 0.48 | 0.30 | -0.10 |
| $k = 3$ | 0.38 | 0.20 | -0.09 | 0.74 | 0.43 | -0.08 | 0.10 | 0.05 | -0.04 |
| $k = 4$ | 0.33 | 0.16 | -0.03 | 0.23 | 0.12 | -0.01 | 0.57 | 0.33 | -0.03 |
| $k = 5$ | 0.44 | 0.21 | -0.04 | 0.93 | 0.51 | -0.06 | 0.48 | 0.22 | -0.02 |
| $k = 6$ | 3.85 | 2.01 | -0.05 | 1.86 | 0.97 | -0.05 | 2.79 | 2.79 | -0.02 |
the channel reproducibility and evaluate the performance of the proposed channel measurement and modeling prototype in the link-level simulation, computer simulations with the parameters listed in Table V were performed. An ideal channel estimation was applied to the simulation. Fig. 11(a) shows the distribution characteristics of the relative path power distribution. As a result of channel reproduction, the path power distribution of the conventional channel model described in Section III was shifted by approximately 9.2, 9.9, and 7.0 dB from the raw data measured with Profiles A, B, and C, respectively, with a reference CDF of 0.5. The path power characteristics obtained with the proposed channel modeling framework agreed well with those of the WRAN delay profile in all cases, and the difference between the measured raw data and simulation results is controlled below 1.1, 0.8, and 0.4 dB, respectively. Fig. 11(b) shows the distribution characteristics of the RMS delay spread. According to the simulation results, the RMS delay spread distribution of the conventional channel model shifted by approximately 1.5, 0.9, and 3.4 µs from the measurement results for Profiles A, B, and C, respectively, with a reference CDF of 0.5. The difference between the measured raw data and the simulation results with the proposed channel modeling algorithm is controlled below 0.1 µs for all profiles.

Fig. 12 shows the BER characteristics obtained using the

![Figure 11](image1.png)

**FIGURE 11.** Statistical characteristics of channel reproduction.

![Figure 12](image2.png)

**FIGURE 12.** BER characteristics of channel reproduction.
channel coefficient reproduction framework. The energy per bit to noise power spectral density ratio ($E_b/N_0$) required to achieve a BER of $10^{-4}$ by applying the conventional channel model described in Section III decreased by approximately 5, 6, and 7 dB from the simulation results for Profiles A, B, and C, respectively. Meanwhile, the difference in the $E_b/N_0$ required to achieve a BER of $10^{-4}$ between the channel production and WRAN channel delay profile was controlled below 1.5, 1.5, and 1 dB for Profiles A, B, and C, respectively. These results indicate that the reproduction performance of the proposed channel modeling framework is significantly higher than that of the conventional channel modeling framework described in Section III. Thus, it was confirmed that the multipath propagation characteristics of the measurement results measured by the proposed channel measurement prototype can be modeled and reproduced with the proposed channel modeling framework.

VI. CONCLUSION

We developed a channel measurement and modeling prototype for mobile IEEE 802.22-based wide area communication systems. The prototype can be implemented completely with software and programmable hardware, which enable simple multipath propagation measurement and modeling in rural areas. Based on the validation results, it was confirmed that the propagation channel measured with the prototype can be modeled and reproduced with excellent statistical characteristics. Owning to its simple implementation and excellent channel modeling and reproducibility, our proposed prototype is expected to enable simple and flexible outdoor channel characterization and transmission performance evaluation for near-future IEEE 802.22-based mobile communication systems.

REFERENCES

[1] Cisco Inc., “Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2017-2022 White Paper,” Feb. 2019.
[2] H. Harada, “White space communication systems: An overview of regulation, standardization and trial,” IEICE Trans. Commun., vol. 97, no. 2, pp. 261-274, Feb. 2014.
[3] IEEE Computer Society, “IEEE Std 802.22™,” Jul. 2012.
[4] K. Hasegawa, et al., “IEEE 802.22-based WRAN system for disaster-resistant network systems,” 2013 IEEE Region 10 Humanitarian Technology Conference., pp. 264–269, Aug. 2013.
[5] T. Matsumura, H. Ueno, K. Mizutani, and H. Harada, “Compact IEEE 802.22-based radio equipment enabling easy installation for regional area network system using TV white-spaces,” Proc. IEEE LANMAN’2017, pp. 264–269, June 2017.
[6] H. Ueno, T. Matsumura, K. Mizutani, and H. Harada, “An implementable channel and CFO estimation scheme for IEEE 802.22-based radio equipment,” in Proc. WCNCW’17, pp. 1–6, Mar. 2017.
[7] R. Ouyang, T. Matsumura, K. Mizutani, and H. Harada, “A robust channel estimation for IEEE 802.22 enabling wide area vehicular communication,” in Proc. WPMC’2018, pp. 52–57, Nov. 2018.
[8] R. Ouyang, T. Masumura, K. Mizutani, and H. Harada, “A reliable channel estimation scheme using scattered pilot pattern for IEEE 802.22-based mobile communication system,” IEEE Trans. on Cogn. Commun. Netw., vol. 5, no. 4, pp. 935–948, Dec. 2019.
[9] A. Bishnu and V. Bhatia, “An IEEE 802.22 transceiver framework and its performance analysis on software defined radio for TV white space,” Telecommun. Syst., vol. 68, no. 4, pp. 657–668, Aug. 2018.
[10] V. Popescu, M. Fadda, M. Murroni, J. Morgade, and P. Angueira, “Co-channel and adjacent channel interference and protection issues for DVB-T2 and IEEE 80.22 WRAN operation,” IEEE Trans. Broadcast., vol. 60, no. 4, pp. 693–700, Dec. 2014.
[11] V. Popescu, M. Fadda, and M. Murroni, “Performance analysis of IEEE 802.22 wireless regional area network in the presence of digital video broadcasting – second generation terrestrial broadcasting services,” IET Commun., vol. 10, pp. 922–928, May 2016.
[12] A. Mohammed and K. Bilal, “Impact of AWGN, Rayleigh and Rician fading channels on BER performance of a cognitive radio network,” Int. J. Eng. Res., vol. 8, pp. 1365–1368, Apr. 2017.
[13] COST 207 Report, “Digital land mobile radio communications,” Commission of European Communities, Directorate General, Telecommunications, Information Industries and Innovation, Luxembourg, Apr. 1990.
[14] A. F. Molisch, Wireless communications, vol. 34, John Wiley & Sons, 2012.
[15] E. Sofer and G. Chouinard, “WRAN channel modeling,” IEEE 802.22-05/0055r7, Aug. 2005.
[16] H. Ohara, et al., “Characterization of broadband mobile communication channel in 200 MHz band based on Saleh-Valenzuela model,” IEICE Trans. Commun. vol. E101. B, no. 11, pp. 2277–2288, Nov. 2018.
[17] 3GPP, “Study on channel model for frequencies from 0.5 to 100 GHz (3GPP TR 38.901 version 16.1.0 Release 16),” Dec. 2019.
[18] International Telecommunication Union, “Guidelines for evaluation of radio interface technologies for IMT-Advanced,” Geneva, Switzerland, Rep. ITU-R M.2135-1, Dec. 2009.
[19] V. Erceg, et al., “Channel models for fixed wireless applications,” IEEE 802.16.3-c/n-07/94r5, July 2001.
[20] International Telecommunication Union, “Guidelines for evaluation of radio transmission technologies for IMT-2000,” Rep. ITU-R M.1225-0, Feb. 1997.
[21] T. S. Rappaport, “Characterization of UHF multipath radio channels in factory buildings,” IEEE Trans. Antennas Propag., vol. 37, no. 8, pp. 1058–1069, Aug. 1989.
[22] Y. Oda, R. Tsuchihashi, K. Tsunekawa, and M. Hara, “Measured path loss and multipath propagation characteristics in UHF and microwave frequency bands for urban mobile communications,” in Proc. IEEE VTS’2001, vol. 1, pp. 337–341, May 2001.
[23] I. Angulo, et al., “A measurement-based multipath channel model for signal propagation in presence of wind farms in the UHF band,” IEEE Trans. Commun., vol. 61, no. 11, pp. 4788–4798, Oct. 2013.
[24] C. K. Stoumpos and M. T. Chryssomallis, “Improvement of channel models performance with parameters values from measurements: a test case for suburban and rural environments at 450 MHz,” IEEE Antennas Wireless Propag. Lett., vol. 17, no. 8, pp. 1396–1400, Jun. 2018.
[25] E. Kassem, et al., “Wideband UHF and SHF long-range channel characterization,” EURASIP J. Wirel. Comm., vol. 2019, no. 1, pp. 1–16, Jul. 2019.
[26] A. Saleh and R. Valenzuela, “A statistical model for indoor multipath propagation,” IEEE J. Sel. Areas Commun., vol. 5, no. 2, pp. 128–137, Feb. 1987.
[27] T. Almohamad, M. Salleh, M. Mahmud, K. Karas, N. Shah, and S. Al-Ali, “Dual-determination of modulation types and signal-to-noise ratios using 2D-ASIQH features for next generation of wireless communication systems,” IEEE Access, vol. 9, pp. 25843–25857, Feb. 2021.
[28] T. Almohamad, M. Salleh, M. Mahmud, and A. Sa’D, “Simultaneous determination of modulation types and signal-to-noise ratios using feature-based approach,” IEEE Access, vol. 6, pp. 9262–9271, Feb. 2018.
[29] J. F. Arthur, “The frequency distribution of the annual maximum (or minimum) values of meteorological elements,” Quarterly J. Royal Meteorological Society, 88(348), pp. 158–171, Apr. 1955.

[30] H. El-Sallabi, M. Abdallah, J. Chamberland, and K. Qaraqe, “A statistical model for delay domain radio channel parameter affected with extreme values,” in Proc. ISAP 2014, pp. 165–166, Dec. 2014.

[31] J. Blumenstein, T. Mikulasek, T. Zemen, C. Mecklenbräuker, R. Marsalek, and A. Prokes, “In-vehicle mm-wave channel model and measurement,” in Proc. IEEE VTC’2014, pp. 1–5, Sep. 2014.

[32] C. L. Hong, I. J. Wassell, G. Athisanisadou, S. Greaves, and M. Sellaris, “Wideband channel measurements and characterization for broadband wireless access,” in Proc. ICAP’2003, vol. 1, pp. 429–432, Nov. 2003.

[33] Z. Yang, J. Wang, M. Han, C. Pan, L. Yang, and Z. Han, “Channel estimation of DMB-T,” in 2002 IEEE Int. Conf. Communications, Circuits and Systems and West Sino Expositions, vol. 2, pp. 1069–1072, Jun. 2002.

[34] N. Czink, P. Cera, J. Salo, E. Bonek, J. Nuutinen, and J. Ylitalo, “A framework for automatic clustering of parametric MIMO channel data including path powers,” in Proc. IEEE VTC’2006, pp. 1–5, Sep. 2006.

[35] S. Ray and R. H. Turi, “Determination of number of clusters in K-means clustering application in colour image segmentation,” in Proc. International Conference on Advances in Pattern Recognition and Digital Techniques, pp. 137–143, Aug. 2000.

[36] N. Czink, et al., “Tracking time-variant cluster parameters in MIMO channel measurements” in Proc. Chinacom 2007, pp. 1147–1151, Aug. 2007.

[37] 3GPP, “3rd Generation Partnership Project; Technical Specification Group (TSG) RAN WG4: Deployment aspects,” Mar. 2000.

[38] R. Ouyang, T. Matsumura, K. Mizutani, and H. Harada, “Channel modeling algorithm for TVWS-based IEEE 802.22 WRAN system in rural areas,” Proc. IEEE VTC2020-Fall, pp. 1–6, Oct. 2020.

[39] W. Jakes, Microwave Mobile Communications, John Wiley & Sons, Inc., 1974.

[40] H. Harada and R. Prasad, Simulation and Software Radio for Mobile Communications, Artech House, 2002.

[41] R. Ouyang, T. Matsumura, K. Mizutani, and H. Harada, “Development of evaluation platform for IEEE 802.22-based highly mobile WRAN communication system with an SDR-based receiver,” in Proc. WPMC’2020, pp. 1–6, Oct. 2020.

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