Wideband Polarimetric Directional Propagation Channel Analysis Inside an Arched Tunnel

Gilbert Siy Ching, Member, IEEE, Mir Ghorashi, Member, IEEE, Markus Landmann, Navarat Lertsirisopon, Jun-ichi Takada, Member, IEEE, Tetsuro Imai, Member, IEEE, Itoji Sameda, and Hironori Sakamoto

Abstract—A wideband directional measurement campaign was managed inside an arched highway tunnel to analyze the radio propagation channel inside such tunnel for future cellular systems in terms of coverage, delay spread and dominant scatterers. Measurements were performed in 3 rounds with different transmitter positions. Using a wideband channel sounder equipped with a cylindrical dual polarized array at the receiver, the spatio-temporal characteristics of the received propagation paths could be estimated by means of a super-resolution estimation algorithm. The extracted paths using this super-resolution algorithm constitute 88% of the total received power. It was also observed that the line-of-sight component (53%) plus single-bounce scattering (26%) comprise up to 79% of the total received power. In other words, more than 90% (i.e. 79% in 88%) of the extracted paths consists of the line-of-sight component and single-bounce scatterings. The strong contribution from single-bounce scattering paths causes the path gain exponent along the tunnel to be larger than $-2$ which is the value for free space. This validates that there is wave guiding effect in the tunnel and coverage is extended relative to open space. The rms delay spreads are generally less than 20 ns and increase when influenced by scattering objects such as jetfans. The dominant scatterers are identified and classified into 6 classes based on the structure of the tunnel and existing objects such as ground, wall, light-frame, ceiling, jetfan and cleaner-parking. It was observed that scattering from ground was dominant among all classified scatterers in all scenarios.

Index Terms—Directional measurements, radio propagation, scatterers, tunnel propagation, wideband channel measurements.

I. INTRODUCTION

In recent years, the fast growth of mobile and wireless technology has affected many aspects of life and industry. As an example, modern generation of transportation industry is extensively being served by wireless technology to improve safety and mobility [1]. On the other hand, as users are relying more on mobile system services, the coverage of cellular phones has become a critical issue for the operators, not only in urban and suburban residential areas but also in suburban and rural roads, and highways. To achieve the best performance of future cellular systems, the analysis of radio propagation channels in such environments is inevitable. This is especially important for mountainous countries with many tunnels in their highway networks. Hence, the radio channel inside tunnels should be treated more carefully.

A number of researches have addressed this subject both theoretically and experimentally. Simulations of the fields inside the tunnel involve two major approaches to model these phenomena. These are the modal analyses [2]–[4] and the geometrical optics based approaches [5]–[11]. Wideband measurements done in recent years have analyzed the root mean square (rms) delay spread [12]–[14] and azimuth-delay power spectrum [8] whereas [15] investigated the possibility of increasing channel capacity through multiple-input-multiple-output (MIMO) systems which might be used for future cellular systems.

For further understanding of the spatio-temporal characteristics of the propagation channel inside an arched tunnel, we have performed a wideband directional sounding for 3 transmitter (Tx) positions [16]. Using a cylindrical antenna array with dual polarized elements at the receiver (Rx), both vertically and horizontally polarized received paths can be analyzed in the spatial domain. A multidimensional maximum likelihood algorithm was used to estimate the parameters of the received propagation paths. To understand the propagation phenomena inside the tunnel, the extracted paths were classified according to the its last interaction in the channel.

Aside from more detailed discussions, we extended our previous results in here to include the power contribution of extracted paths and to identify the dominant propagation micromechanisms. In addition, prediction of received power by simulating standard antennas at the Rx is also included. This gives us an idea of the coverage for each Tx position. Furthermore, the delay spread which relates to the maximum date rate without equalization is also predicted. The directional super-resolution analysis of the propagation channel inside the tunnel presented in this paper is the first of its kind to the best of the authors’ knowledge.

Before proceeding to the next sections, it is necessary to notify the reader that throughout this paper the term “scattering” is used to express any kind of interaction between propagating wave and the structure of the tunnel or existing objects in the channel unless otherwise mentioned. The paper is organized as follows. The details of the measurement campaign are presented...
TABLE I
MEASUREMENT PARAMETERS

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center frequency</td>
<td>5.2 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>100 MHz</td>
</tr>
<tr>
<td>Delay resolution</td>
<td>10 ns</td>
</tr>
<tr>
<td>Maximum delay</td>
<td>3.2 μs</td>
</tr>
<tr>
<td>Tx signal</td>
<td>multitone</td>
</tr>
<tr>
<td>Tx power</td>
<td>40 dBm</td>
</tr>
<tr>
<td>Tx antenna</td>
<td>vertically aligned sleeve dipole</td>
</tr>
<tr>
<td>Tx antenna height</td>
<td>8 m (Tx1), 2.5 m (Tx2 and Tx3)</td>
</tr>
<tr>
<td>Rx antenna array</td>
<td>cylindrical, 4 rings × 24 dual polarized patch elements</td>
</tr>
<tr>
<td>Rx antenna height</td>
<td>2.5 m</td>
</tr>
<tr>
<td>Rx points</td>
<td>14 points (7 points) along tunnel with 25 m (50 m) separation between points for Tx1 (Tx2 and Tx3)</td>
</tr>
<tr>
<td>Synchronization</td>
<td>Cesium clocks</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>25 dB min</td>
</tr>
<tr>
<td>Noise floor</td>
<td>&lt; -85 dBm</td>
</tr>
</tbody>
</table>

in Section II. In Section III, the parameter estimation process is described. This includes the identification of single-bounce scatterings (i.e. Tx to tunnel object/structure to Rx), multiscattering paths and classification of the dominant scatterers. The power contribution of the identified propagation micromechanisms are discussed in Section IV. The prediction of the received power by simulating standard antennas at the Rx is presented as well. These are followed by an analysis of the delay spread in each measurement point. In Section V, detailed analysis of the scatterers by comparing their path gains are discussed for each measurement round. Section VI summarizes the conclusions.

II. MEASUREMENT EQUIPMENT AND SCENARIO

A measurement campaign was managed in a highway tunnel in the second Tomei highway, Shizuoka prefecture, Japan. In the following subsections we will describe the employed equipment and the measurement scenario.

A. Equipment

The RUSK-DoCoMo channel sounder [17] was employed to accomplish the measurements. The related parameters can be found in Table I. The sounding signal is a wideband multitone of 100 MHz bandwidth centered at 5.2 GHz, providing a delay resolution of 10 ns. A vertical sleeve dipole was employed at the Tx whereas the Rx antenna array was composed of 96 dual-polarized patches constituting 4 rings of 24 dual-polarized elements each.

To eliminate the frequency response of the system and cables, the calibration function incorporated in the sounder was used before making measurements, by connecting the Tx and Rx back-to-back. During measurements, the channel impulse response was taken from each Rx element using a fast RF switch and stored in a hard disk for off-line processing. Cesium clocks were used at both Tx and Rx for synchronization. With the employed Rx antenna array, both vertically and horizontally polarized received waves could be analyzed. As the Tx antenna is always vertically aligned, vertical and horizontal polarizations are called copolarization and cross-polarization throughout the paper.

B. Scenario

The tunnel where the measurements were accomplished can accommodate up to 3 car lanes and has a semicircular arched cross section. It is 16.6 m wide on the ground level and has a maximum height of 8.5 m at the center of the cross section. At the measurement time, the tunnel was still under construction but some structures were already installed as shown in Fig. 1(a) with their locations illustrated in Fig. 1(b). The existing objects are as follows:

• jetfan; large ventilators located between Rx2 and Rx3 and between Rx6 and Rx7;
• cleaner-parking; an elevated structure near the ceiling similar to the jetfan, located on Rx12 that is used to park a robot cleaner;
• light-frame; the framing for the lights and cable racks.

Moreover, for the scatterer identification in next sections, we classify the tunnel structure according to Fig. 1(a) as follows:

• ground; the floor of the tunnel;
• ceiling; defined as the portion above the light-frames;
• wall; defined as the portion between light-frames and the ground. Tiles cover the lower half portion of the walls.

The measurement scenario where the experiment was performed in 3 rounds is depicted in Fig. 2. For the first round, the Tx antenna was mounted at the center of the cross section near the ceiling at a height of 8 m from the ground (Tx1). For the second and third rounds, Tx was installed on a tripod with a height of 2.5 m from the ground. For the second round, Tx2 was
In this study, the extracted discrete paths constitute 88% of the received power. The remaining 12% of the received power are the dense multipath components. Furthermore, having AoA for each extracted path, the Rx antenna array gain could be de-convolved from the estimated data [19].

B. The Strongest Extracted Path

Even though a super-resolution parameter estimator was used, the estimation of the LoS component from the measurement data is possible only if there is no scattering near the Tx antenna. In other words, if a scattering is happening too close (in both delay and angle dimensions) to the Tx antenna, it may not be resolvable from the LoS component. Apparently for Tx1, the ceiling specular reflection happens very close to the Tx antenna which makes it unresolvable from the LoS component. But for other ceiling scatterings which are not specular, it can still be detected. For Tx2 (beyond Rx position of 50 m) and Tx3, the same happens for ground specular reflection, although ground scatterings which are not specular can still be detected.

Consequently, ceiling specular reflections were not detected for Tx1, ground specular reflections were also not detected beyond Tx and Rx separation of 75 m. For Tx2, ceiling and ground specular reflections were not detected beyond 50 m. For Tx3 in which the Tx antenna was positioned near the wall, ground specular reflections were not resolvable from the LoS component.

C. Classification of Extracted Paths

The extracted paths are classified according to the objects/structure introduced in Section II-B. By tracing the AoA from the Rx towards the tunnel, the last scattering point of each extracted path can be identified. This scattering point is then used to classify the extracted path. In addition to the AoA, the delay helps to confirm if the extracted path is a single-bounce scattering (i.e. Tx to tunnel object/structure to Rx) or multisattering. Note that single-bounce scattering or multisattering can be due to any kind of propagation mechanism, which includes specular reflections, non-specular reflections, diffractions, etc.

Table II shows the extracted paths and their estimated parameters for Tx1-Rx2 where the delay $\tau$ is expressed as the corresponding path length $cT$ in meters, where $c$ is the speed of light. We used Tx1-Rx2 because at this point, scattering from several objects/structures were observed. The $g_{N}$ and $g_{H}$ represent the estimated path gains for the copolarized and cross-polarized components of the extracted path respectively and are defined as

$$g_{N,I} = |\gamma_{N,I}|^2$$
$$g_{H,I} = |\gamma_{H,I}|^2$$

The path gain $g_{t}$ is also available by the relation

$$g_{t} = |\gamma_{N,I}|^2 + |\gamma_{H,I}|^2$$

The values in parenthesis in Table II represent the theoretical values for LoS and ground specular reflection. The computation of the theoretical LoS path gain uses a vertically aligned $\lambda/2$ dipole at Tx, and the Friis transmission equation given by
TABLE II

<table>
<thead>
<tr>
<th>path index</th>
<th>$g$ [dB]</th>
<th>$\tau$ [m]</th>
<th>$\varphi$ [deg]</th>
<th>$\vartheta$ [deg]</th>
<th>$g_v$ [dB]</th>
<th>$g_H$ [dB]</th>
<th>scatterer (bounce type)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-82</td>
<td>50</td>
<td>0</td>
<td>84</td>
<td>-83</td>
<td>-100</td>
<td>strongest path</td>
</tr>
<tr>
<td>2</td>
<td>-93</td>
<td>52</td>
<td>16</td>
<td>88</td>
<td>-93</td>
<td>-105</td>
<td>wall</td>
</tr>
<tr>
<td>3</td>
<td>-95</td>
<td>52</td>
<td>-15</td>
<td>83</td>
<td>-98</td>
<td>-98</td>
<td>light-frame</td>
</tr>
<tr>
<td>4</td>
<td>-96</td>
<td>54</td>
<td>-21</td>
<td>97</td>
<td>-97</td>
<td>-102</td>
<td>ground</td>
</tr>
<tr>
<td>5</td>
<td>-96</td>
<td>51</td>
<td>-1</td>
<td>102</td>
<td>-98</td>
<td>-101</td>
<td>ground</td>
</tr>
<tr>
<td>6</td>
<td>-99</td>
<td>54</td>
<td>23</td>
<td>99</td>
<td>-99</td>
<td>-120</td>
<td>ground</td>
</tr>
<tr>
<td>7</td>
<td>-101</td>
<td>55</td>
<td>13</td>
<td>76</td>
<td>-110</td>
<td>-101</td>
<td>ceiling (multiscattering)</td>
</tr>
</tbody>
</table>

where $r$ is the separation of Tx and Rx. The dielectric constant and conductivity of ground is assumed to be 30 and 0.03 S/m respectively [20]. Fig. 3 shows the last scattering point for each of the extracted paths for Tx1-Rx2 in which indexes follow those of Table II. Furthermore, Fig. 4 shows the impulse response of the top peaks after identifying scatterers for Tx1-Rx2. These peaks are consistent with the identified scatterers listed in Table II.

**IV. POWER CONTRIBUTION**

**A. Propagation Micromechanisms**

The contribution of the propagation micromechanisms for Tx1 is shown in Fig. 5 based on the following equation:

$$\text{Micromechanism contribution} = \frac{\sum_{i \in C_j} G_i}{\sum_{i=1}^{L} G_i}$$  \hspace{1cm} (6)

where $C_j$ corresponds to the $j$th scatterer class set where the extracted path $l$ belongs. SB in the figure corresponds to single-bounce scattering. Note that as mentioned in the previous section, single-bounce scattering can be due to any kind of propagation mechanism. Therefore even though specular reflections were not detected beyond certain Rx positions, SB can still exist and will be composed of non-specular components beyond these positions.

In the classification of the extracted paths, only those paths whose gains are within 20 dB from the path gain of the strongest path were considered. Those paths which are not considered in this process are indicated as “unclassified paths.” “Van-scattering” corresponds to paths whose last scattering point is the roof-top of the measurement van where the Rx antenna array was mounted. Van-scatterings were neither classified as single-bounce scattering nor multiscattering since the measurement van is not part of the tunnel structure.

Table III shows the contribution of the strongest path, single-bounce scattering and multiscatterings among others to the total path gain of the extracted paths in each measurement round. In general, the strongest path comprise on the average 60% of the total path gain. The combined single-bounce scatterings on
TABLE III
Propagation Micromechanism Contribution in Each Measurement Round

<table>
<thead>
<tr>
<th>Tx</th>
<th>strongest path</th>
<th>single-bounce</th>
<th>multisattering</th>
<th>unclassified</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tx1</td>
<td>59%</td>
<td>33%</td>
<td>1%</td>
<td>5%</td>
</tr>
<tr>
<td>Tx2</td>
<td>56%</td>
<td>32%</td>
<td>10%</td>
<td>1%</td>
</tr>
<tr>
<td>Tx3</td>
<td>65%</td>
<td>22%</td>
<td>8%</td>
<td>3%</td>
</tr>
</tbody>
</table>

the other hand comprise on the average close to 30% of the total path gain whereas the multiscatterings comprise 5% on the average. Single-bounce scatterings contribute more than the multiscatterings since each bounce results in an additional loss in the path to the tunnel object/structure.

The analyses of the data from all measurement points show that scattering from light-frame, jetfan, and cleaner-parking are always single-bounce whereas scattering from ground, wall, and ceiling can be multiscattering as well.

B. Prediction of the Received Power

In this subsection, received power along the tunnel is predicted by assuming standard antennas at Rx. The result gives us an idea of the coverage for each Tx position. Using the estimated parameters of the extracted paths, the received power at position $s$ is predicted by

$$P(s) = \sum_{l=1}^{L(s)} (\gamma_N b_N(\varphi_l, \vartheta_l) + \gamma_H b_H(\varphi_l, \vartheta_l))^2 P_T$$ (7)

where $b_N$ and $b_H$ are the complex antenna response of an assumed standard Rx antenna in the direction of the incoming path for vertical and horizontal polarization components respectively, and $P_T$ is the transmitted power.

To calculate the copolarized received power, a vertically aligned $\lambda/2$ dipole ($b_H = 0$) was simulated as the standard Rx antenna, and to get the cross-polarized received power, a vertically aligned $\lambda/2$ magnetic dipole ($b_N = 0$) was simulated. It is noted that the same antenna pattern as the $\lambda/2$ magnetic dipole can be realized by the slotted cylinder antenna with a diameter of $\lambda/8$ [21]. Here $P_T$ is assumed to be 0 dBm. To evaluate the contribution of strongest path and single-bounce scatterings, the received power by these paths are compared to the received power via all classified paths.

Fig. 6 shows the predicted received power for Tx1 as a function of the horizontal distance from Tx. For comparison, the theoretical LoS using the Friis transmission equation with vertical $\lambda/2$ dipoles on both Tx and Rx is also shown. The results show that the trend of the “strongest path and single-bounce scattering” approximates well the trend of the “all classified paths” for both copolarized and cross-polarized received power. The same trend was also observed for the other measurement rounds of Tx2 and Tx3. We note that due to the phase cancellation of the extracted paths, the received power of the “strongest path and single-bounce scattering” sometimes exceeds the received power of the “all classified paths.”

The observation in other works that the received power versus distance between Tx and Rx can be divided into two zones with the zone near the Tx having a steeper slope [22] was not observed in this study. This may be due to the large separation of the Rx points. Nevertheless, the path gain exponent of copolarized received power for all measurement rounds as shown in Table IV is greater than -2. This indicates that there is wave guiding effect in the tunnel and is consistent with the literature [23]. Moreover, when the path gain exponent is close to -2, it means energy is spread out over a larger area as distance is increased. On the other hand, when the path gain exponent is near 0, it means energy is more guided. As a result, the path gain exponent of Tx2 and Tx3 is closer to -2 than Tx1 since Tx1 is located near the ceiling and energy is more confined as compared to Tx2 and Tx3. Finally, we note that the path gain exponent of the “strongest path and single-bounce scattering” is similar to the “all classified paths.”

C. Delay Spread

To predict the root mean square (rms) delay spread for copolarized and cross-polarized waves, $\lambda/2$ electric and magnetic dipole antennas were assumed as the Rx antennas respectively and the rms delay spreads are computed as follows:

$$\tau_{\text{rms},\ell}(s) = \sqrt{\frac{\sum_{l=1}^{L(s)} \left( \tau_l - \tau_{\text{rms},\ell}(s) \right)^2 \mathcal{G}(\varphi_l, \vartheta_l) \delta_{\ell,l} }{\sum_{l=1}^{L(s)} \mathcal{G}(\varphi_l, \vartheta_l) \delta_{\ell,l} }}$$ (8)

where

$$\tau_{\text{rms},\ell}(s) = \frac{\sum_{l=1}^{L(s)} \mathcal{G}(\varphi_l, \vartheta_l) \delta_{\ell,l} }{\sum_{l=1}^{L(s)} \mathcal{G}(\varphi_l, \vartheta_l) \delta_{\ell,l} }$$ (9)

is the mean delay, $\alpha = \{V, H\}$, and $g(\varphi_l, \vartheta_l)$ is the Rx antenna gain for the incoming path.
Fig. 7 shows the derived rms delay spreads for Tx1 as a function of the horizontal distance from Tx. It can be observed that the trend of the rms delay spread initially increases and then decreases as Rx moves further away from Tx for both polarizations. Looking at Fig. 1(b), jetfans occupying the upper portion of the tunnel are located between Rx6 and Rx7, at 160 m from Tx. These can act like a reflecting wall and when Rx moves closer to it, the rms delay spread will initially increase until it reaches the middle of Tx and the reflecting wall, and then decrease as it reaches the reflecting wall. This behavior is common in LOS microcell scenarios [24]. The increase in rms delay spread at 250 and 275 m on the other hand is due to the cleaner-parking situated also near the upper portion of the tunnel at around 300 m away from Tx. For the other Rx points which do not receive scattered waves from the jetfan or the cleaner-parking, the rms delay spread is less than 20 ns since only paths with delays close to the delay of the LoS path contribute to the rms delay spread.

Fig. 8 shows the rms delay spreads for Tx2 and it has the same trend as Fig. 7. However, the first peaks are lower than that of Tx1. This can be due to the lower height of the Tx antenna in Tx2 compared to Tx1. The second peaks appearing in Fig. 8 are larger than the one in Tx1. This may be a consequence of obstruction of the cleaner-parking by the jetfan in the Tx1 case. For Tx3, almost similar results as Tx2 were observed. The rms delay spread values are consistent with the observations in [5].

The rms delay spreads derived from the “strongest path and single-bounce scattering” were also calculated and the values included in Figs. 7 to 8. It can be observed that the “strongest path and single-bounce scattering” approximates the “all classified paths” generally well for both copolarized and cross-polarized received waves.

V. SCATTERER ANALYSIS

The scatterer class contribution is considered as the superposition of the extracted path gains belonging to that scatterer class:

\[
\text{Scatterer class contribution} = \sum_{k \in C_k} g_k
\]

where \(C_k\) is the \(k\)th scatterer class. The calculated scatterer class contribution for all Rx points in measurement rounds Tx1 and Tx2 are shown in Figs. 9 and 10 respectively. The theoretical LoS gain assuming a vertically aligned \(\lambda/2\) dipole at the Tx was also calculated using the Friis transmission equation. The strongest path differs from the theoretical LoS as discussed in
Section III-B. It can be observed from Fig. 9 that there are strong contributions from ground and light-frame scatterers for Tx1. The light-frame scattering is usually single-bounce whereas the ground scattering includes multiscattering as well.

Fig. 10 shows the scatterer class contributions for Tx2 where the measurements were taken at 50 m intervals. The gain of the strongest path deviates from the theoretical LoS path gain as distance increases because the ground specular and ceiling specular reflections become unresolvable from the theoretical LoS path. Here the ground scatterers dominate too, similar to Tx1, but on the other hand, wall scatterers are more significant than light-frame scatterers especially at 100, 150 and 200 m. This may be due to the position of Tx2 which is located at the ground level and illuminates the walls more, as opposed to Tx1 which is located near the ceiling and illuminates the light-frames more than the walls.

For Tx3, measurements were also taken at every 50 m intervals with the ground, wall, and light-frame scatterers having high power contributions. One significant difference in its scatter class contribution compared to previous rounds is that there are no ceiling scatterers detected for any Rx position. This might be due to the position of Tx3 relative to the arched cross section of the tunnel. For Tx1 and Tx2, since Tx antenna as well as the Rx antenna array are positioned in the middle of the tunnel cross section, paths can bounce to the ground and then ceiling before arriving at the Rx antenna array. For Tx3 in which the Tx antenna is located beside the wall of the tunnel, scattering from the ceiling cannot reach the Rx points due to the curved structure of the tunnel.

For all Tx cases, it was observed that scattering from light-frame, jetfan, and the cleaner-parking are single-bounce whereas the contribution from ground, wall, and ceiling can be multiscattering as well. The jetfan and cleaner-parking scatterers are dominant only for Rx points close to them. As Tx and Rx separation increases, the power of some scatterers become comparable to the power of the strongest path which causes the path gain exponent along the tunnel to differ from -2. Generally, it seems that the arched cross section of the tunnel converges the paths toward the ground, which causes the dominance of ground scattering in most measurement points.

VI. CONCLUSION

We analyzed the spatio-temporal radio propagation channel inside an arched highway tunnel employing a wideband directional channel sounding data for future cellular systems in terms of coverage, delay spread and dominant scatterers. The measurements were accomplished in 3 rounds with different Tx positions. The extracted paths using this super-resolution algorithm constitute 88% of the total received power. It was also observed that the LoS component (53%) plus single-bounce scattering (26%) comprise up to 79% of the total received power.

The strong contribution from single-bounce scattering paths causes the path gain exponent along the tunnel to be larger than -2 which is the value for free space. This indicates that there is wave guiding effect in the tunnel and coverage is extended relative to open space. Moreover, Tx1 which is located near the ceiling has more guiding effect than Tx2 and Tx3. The rms delay spreads are generally less than 20 ns and increase to more than 100 ns when influenced by scattering objects such as jetfans. Since it is known as a rule of thumb that no equalizer is needed when the delay spread is less than 1/10 of the symbol duration, symbol rates of up to around 1 Msymbol/s can be achieved without equalization [23].

The dominant scatterers were identified and classified into 6 classes based on the structure of the tunnel and existing objects such as ground, wall, light-frame, ceiling, jetfan and cleaner-parking. It was observed that scattering from ground was dominant among all classified scatterers in all scenarios. Another observation is that scattering from light-frame, jetfan, and cleaner-parking are single-bounce whereas contribution from ground, wall, and ceiling can be multiscattering as well.

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REFERENCES

Gilbert Siy Ching (S’98–M’07) was born in Manila, Philippines, in 1974. He received the B.S. and M.S. degrees in electrical engineering from the University of the Philippines, in 1996 and 2003, respectively, and the D.E. degree from the Tokyo Institute of Technology, Tokyo, Japan in 2007.

From 1996 to 2003, he was also an Instructor at the University of the Philippines. Since 2007, he has been working as a Researcher and Instructor at Ilmenau University of Technology. His current interests are in radio propagation channel measurements, analysis and modeling.

Dr. Ching was the recipient of one of the best student paper awards in PIMRC '06 and ITS '07. He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE), Japan.

Mir Ghoraishi (S’99–M’05) received the B.E. degree from Isfahan University of Technology, Isfahan, Iran and the M.E. degree from Amirkabir University of Technology, Tehran, Iran, in 1993 and 1999 respectively, and the Ph.D. degree from the Tokyo Institute of Technology, Tokyo, Japan, in 2005.

Since 1999, he has been with the Tokyo Institute of Technology, where he has been a Senior Researcher since 2004. His research interests are radio channel analysis and modeling, parameter estimation algorithms and positioning and tracking of wireless nodes and objects.

Dr. Ghoraishi is a member of the Institute of Electronics, Information and Communication Engineers of Japan (IEICE).

Markus Landmann was born in Zeitz, Germany in 1977. He received the Dipl.-Ing. (M.S.E.E.) and Dr.-Ing. (Ph.D.E.E.) degrees in electrical engineering (information technology) from Ilmenau University of Technology, Germany, in 2001 and 2008 respectively.

From 2001 to 2003, he was working as a Research Assistant and Instructor at Ilmenau University of Technology. In 2004, he was developing advanced antenna array calibration methods and high resolution parameter estimation algorithm (RIMAX) for propagation studies at MEDAV Company. In 2005, he was a Visiting Researcher and Instructor at Tokyo Institute of Technology (Takada Laboratory) in the field of channel measurement and estimation techniques. From 2006 to 2008, he was finalizing his Ph.D. thesis as a Research Assistant and Instructor at Ilmenau University of Technology. His current interests are wireless propagation, channel modeling, and array signal processing.

Navarat Lertsirisopon was born in Bangkok, Thailand, in 1981. She received the B.E. degree from Sirindhorn International Institute of Technology, Thammasat University, Bangkok, Thailand, in 2002 and the M.E. degree from Tokyo Institute of Technology, Tokyo, Japan in 2006, where she is working toward the D.E. degree.

Her current research interest is propagation prediction modeling in wireless communication systems. Ms. Lertsirisopon is a student member of the Institute of Electronics, Information and Communication Engineers (IEICE), Japan.

Jun-ichi Takada (S’89–M’93) received the B.E., M.E., and D.E. degrees from the Tokyo Institute of Technology, Tokyo, Japan, in 1987, 1989, and 1992 respectively.

From 1992 to 1994, he was a Research Associate Professor at Chiba University, Chiba, Japan. From 1994 to 2006, he was an Associate Professor at the Tokyo Institute of Technology where, since 2006, he has been a Professor. His current interests are wireless propagation and channel modeling, array signal processing, UWB radio, cognitive radio, and ICT for international development.

Dr. Takada is a member of IEICE, ACES, and the ECTI Association Thailand.

Tetsuro Imai (M’93) was born in Tochigi, Japan, in 1967. He received the B.S. and Ph.D. degrees from Tokohu University, Japan, in 1991 and 2002, respectively.

He joined the Wireless System Laboratories, Nippon Telegraph and Telephone Corporation (NTT), Kanagawa, Japan, in 1991. Since then, he has been engaged in the research and development of radio propagation and system design for mobile communications. He is now Manager of the Radio Access Network Development Department, NTT DOCOMO, Inc., Kanagawa, Japan.

Dr. Imai is a Member of the Institute of Electronics, Information and Communication Engineers of Japan (IEICE).

Itoji Sameda was born in Oita, Japan in 1968. She received the B.S and M.S degrees in electrical and electronics engineering from Nagasaki University, Nagasaki, Japan, in 1992 and 1994 respectively.

She joined the Japan Highway Public Corporation in 1994. In 2005, the company was privatized and she is now with the Electronic Toll Collection (ETC) System Section, Expressway Operation Department, Kansai branch of West Nippon Expressway Co. Ltd. Her research interest include wireless communication systems.

Hironori Sakamoto is with the Highway Telecom Engineering Co. Ltd., Japan.

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