UWB Propagation Measurements in Vehicular Environments

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Abstract—The characteristics of ultra-wideband (UWB) channels in vehicular environments are explored. A set of propagation measurements were conducted on roadways and in underground parking garages and the resulting propagation data consists of approximately 1,200 multipath profiles. The channel impulse responses are estimated from the measured data using generalized maximum likelihood. The statistics of channel parameters, including arrival times and amplitudes of multipath components, are examined and a modified Saleh-Valenzuela model is fit to the measured characteristics.

I. INTRODUCTION

Vehicular applications of ultra-wideband (UWB) technology have attracted considerable attention. Vehicle-to-vehicle communication, one of the important facets of intelligent car transportation systems, is expected to enhance car safety. Even though a 5.9 GHz band is currently allocated for dedicated short range communications (DSRC), other wireless technologies such as UWB can augment existing ones. Vehicular radar is used to assist cruise control and collision avoidance and UWB is considered to be a solution because of its extremely fine range resolution [1].

Understanding channel characteristics for vehicular environments is important for a robust system design. Narrowband vehicle-to-vehicle channels have been studied by several researchers [2]-[5]. Some have reported on intra-vehicle channel characterization for UWB [6], [7]. In this work, we examine the properties of UWB channels in vehicular environments, such as outdoor roadways and indoor parking garages. A set of time domain measurements are made and based on the measurement data set, the statistical characteristics of the channel are discussed. In Section II, a detailed description of the measurement procedure is presented. Statistical modeling is discussed in Section III.

II. MEASUREMENT CAMPAIGN

A. Measurement System

A measurement campaign was carried out in both outdoor and indoor environments. A Time Domain P 210 evaluation kit was used to obtain channel responses. The scanning receiver system employs multiple in-phase and quadrature correlator pairs to achieve synchronization and scanning of the waveform [8]. The tracking correlators synchronize with and track the received pulse train. The scanning correlators sample the received signal relative to the lock spot established by the tracking correlators. This enables capture of the received waveform, without a wired connection between the transmitting and receiving sides, to supply a common trigger signal. Vertically polarized dipole antennas are used in the system. The transceivers were mounted 2 ft above the ground, which is the approximate height of a vehicle’s grille or bumper. UWB pulses were emitted by the transmitter every 10 µsec and the received waveform was averaged over 1,024 traces to improve the signal quality. Each waveform was captured at a 78.65 GHz sampling rate. Figure 1 shows a normalized plot of the UWB pulse received at 3 m with a clear line-of-sight (LoS), as well as its spectral density. The frequencies of 10 dB emission points are 3.28 GHz and 5.03 GHz. This waveform was used as a correlator template signal and was modeled by

\[ w(t) = \exp \left(-at^2\right) \sin(\omega t), \]

where \( a = 5.55 \) and \( \omega = 26.15 \).
B. Measurement Plan

We classified the channel environments into the following three channel modes (CM).

1) CM 1: outdoor roadways / 2.5 m - 20 m.
2) CM 2: outdoor roadways / 30 m - 80 m.
3) CM 3: underground parking garages / 2.5 m - 20 m.

All measurements were made with a clear LoS and the channel was assumed to be stationary during the test. Regarding the tests for CM 1 and 2, we chose 67 fixed sites on roadways in the city of Pohang, Korea, including the campus driveways of Handong University and Pohang College. At each site, we took samples at different locations with a 2.5 m distance between each, while the receiver was fixed at one location. For safety purposes, we selected roadways where traffic was light and we placed vehicles around the transceivers to simulate traffic situations. Exemplary test plans are shown in Figure 2. For CM 3, samples were taken in the underground parking garages of 5 apartment complexes. The total number of measured signals in CM 1, 2, and 3 were 425, 388, and 396, respectively. Exemplary channel profiles are shown in Figure 3. We can observe that the first path arrives at approximately 10 ns in all cases, regardless of range. This is because the initial lock point is established near the first arriving path which is the strongest, and the sampling is performed relative to it. Figure 4 shows the sequences of spatially adjacent power delay profiles measured in CM 2.

III. Multipath Statistics

A. Number of Major Paths

Channel impulse responses were obtained by deconvolving the template waveform \( w(t) \) from the measured signals. The generalized maximum likelihood was used to estimate the impulse responses. An iterative nonlinear programming technique was employed, by which the unknown parameters were estimated in a sequential manner [1], [9]. Specifically, the arrival time of each component signal was individually estimated while all other parameters were fixed. This algorithm can be regarded as a special
TABLE I
STATISTICS FOR THE NUMBER OF PATHS WITHIN 16 dB OF THE PEAK

<table>
<thead>
<tr>
<th>channel mode</th>
<th>mean</th>
<th>standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM 1</td>
<td>43.5</td>
<td>15.8</td>
</tr>
<tr>
<td>CM 2</td>
<td>55.5</td>
<td>27.5</td>
</tr>
<tr>
<td>CM 3</td>
<td>75.4</td>
<td>26.4</td>
</tr>
</tbody>
</table>

The case of the CLEAN algorithm [10]. The iterative search process stopped when no more paths greater than 2.5% (16 dB) of the peak amplitude were detected. The number of major paths within 16 dB of the peak, namely $N_m$, was counted for each profile. Means and standard deviations of $N_m$ in each channel mode are summarized in Table I. In outdoor environments, the mean of $N_m$ is greater in CM 2 than in CM 1, which indicates that it increases with the range.

B. Path Arrivals

For the path arrivals, we can consider the Poisson distribution as a preliminary model. Table II summarizes arrival rates in each channel mode. These parameters were obtained by measuring mean inter-arrival times. However, because of the clustering effect of path arrivals, the Poisson model did not result in a very good fit. The UWB channel models suggested by IEEE 802.15.3a and 802.15.4a standardization groups [11], [12] take clustering effects into account. According to this model, the channel impulse response $h(t)$ is generally represented by

$$h(t) = \sum_{l=0}^{L} \sum_{k=0}^{K} \alpha_{k,l} \delta(t - T_l - \tau_{k,l}),$$

(2)

where $T_l$ is the delay of the $l$th cluster. The parameter $\tau_{k,l}$ is the delay of the ray relative to the cluster arrival time and $\alpha_{k,l}$ denotes the path strength. The subscript $\{k,l\}$ indicates that the quantities depend on the $l$th cluster and $k$th ray. We did not consider shadowing in this work. Cluster and ray arrivals are modeled as Poisson processes with different arrival rates. However, identifying clusters in the measured data is a very difficult task. We carried this out manually by applying a sliding window to the energy profile of each signal [10]. Exemplary cluster maps are reproduced in Figure 5. In most cases, more clusters were observed in indoor data than in outdoor data. This is probably because more complex multipath structures exist indoors. Cluster and ray arrival rates in each channel mode are summarized in Table III.

C. Amplitude Statistics

Path strength is assumed to follow lognormal fading, with its mean energy decreasing exponentially with excess delay [11],

$$E[|\alpha_{k,l}|^2] = \Omega_0 e^{-T_l/\Gamma} e^{-\tau_{k,l}/\gamma},$$

(3)

where $\Gamma$ and $\gamma$ are cluster and ray decay factors, respectively, and $\Omega_0$ is a constant. Decay factors can be found by applying a linear regression technique to channel coefficients collected from all measured signals in each channel mode. The ray decay factor $\gamma$ can be determined by finding the least square fit to the logarithmic decay slope of ray energies, as shown in Figure 6. The excess delay was calibrated relative to the first arriving ray in each cluster. Instead of normalizing the ray amplitudes within the cluster with respect to the peak amplitude or the strength of the first arriving path, we scaled them such that the resulting squared error was minimized. The optimal ray

TABLE II
PATH ARRIVAL RATE

<table>
<thead>
<tr>
<th>channel mode</th>
<th>arrival rate (1/ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM 1</td>
<td>0.4714</td>
</tr>
<tr>
<td>CM 2</td>
<td>0.4658</td>
</tr>
<tr>
<td>CM 3</td>
<td>0.5511</td>
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</table>

TABLE III
CLUSTER AND RAY ARRIVAL RATES

<table>
<thead>
<tr>
<th>channel mode</th>
<th>$\Lambda$ (1/ns)</th>
<th>$\lambda$ (1/ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM 1</td>
<td>0.0485</td>
<td>1.2587</td>
</tr>
<tr>
<td>CM 2</td>
<td>0.0390</td>
<td>1.0496</td>
</tr>
<tr>
<td>CM 3</td>
<td>0.0324</td>
<td>1.0791</td>
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TABLE IV
FADING PARAMETERS

<table>
<thead>
<tr>
<th>parameter</th>
<th>CM 1</th>
<th>CM 2</th>
<th>CM 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Gamma )</td>
<td>39.02</td>
<td>58.02</td>
<td>49.10</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>6.81</td>
<td>18.90</td>
<td>11.29</td>
</tr>
<tr>
<td>( \sigma_1 )</td>
<td>3.62</td>
<td>3.22</td>
<td>2.68</td>
</tr>
<tr>
<td>( \sigma_2 )</td>
<td>6.19</td>
<td>6.12</td>
<td>5.87</td>
</tr>
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</table>

in our test. It would be useful to collect propagation data in different environments, such as tunnels. It would be also interesting to apply other theoretical models, such as \( \Delta - K \) model, to the measured data and compare the fitness.

V. ACKNOWLEDGEMENTS

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