Understanding the Ultrawideband Channel Characteristics Within a Computer Chassis

Stephen Redfield, Sirikarn Woracheewan, Huaping Liu, Patrick Chiang, Jay Nejedlo, and Rahul Khanna

Abstract—A measurement-based, statistical ultrawideband (UWB) channel model is presented for the unique environment within a computer chassis. The channel impulse response parameters are derived from measurement data. Because of the short-range communications, a mixture of near-field and far-field propagation is characterized by the use of a breakpoint path-loss model. Due to the near-field nature of this environment, an unusually large number of clusters and rapid cluster decay time is noted in the channel impulse response. Additionally, electromagnetic interference measured inside a computer chassis that is generated by the motherboard in a custom fully operational mode is presented, wherein it is observed that the CPU clock does not appear as a significant interference source.

Index Terms—Near- and far-field propagation, statistical channel model, ultrawideband (UWB).

I. INTRODUCTION

While the use of wireless communications has become ubiquitous for a variety of military, commercial, and consumer applications, the benefits of wireless connectivity within an enclosed computing environment have not been fully explored. The confines of a computer chassis present new opportunities for major improvements in cost, reconfigurability, performance, and platform testability [1]. Currently, the joint test action group (JTAG) daisy-chain boundary scan architecture is used to determine package placement, connection, reliability, and functionality. By replacing these wired interconnects with a broadcast wireless network, up to five JTAG pins per chip could be eliminated, reducing cost and routing complexity. However, the inside of a computer is a complex and challenging environment for wireless communications. A full-size desktop chassis typically houses substantial amounts of metallic objects and is comprised of a highly reflective metallic case. Signals within the enclosed area will experience dense multipath. Because the majority of transmissions are within a short distance of less than 20 cm and exhibit nonuniform forms among the set of computer integrated circuits (IC) on the motherboard, wireless communications below 10 GHz experience a mixture of near- and far-field propagation.

Fig. 1 depicts one usage scenario for in-chassis communications, where an assortment of chips, both transmitting and receiving, are exchanging information within the environment of interest at distances to which this model applies. Pulsed ultrawideband (UWB) [2]–[4] signals’ characteristic multipath resiliency and short-range applicability [3] make it a viable candidate for communications in this environment. Its large bandwidth also makes it suitable for the multiuser scenario [2] required by the numerous IC nodes within the computer.

This letter addresses channel characterization of pulsed UWB systems operating within this unique environment [1]. Channel models for UWB communications have been well characterized, specifically focused on modeling generic 3–10-GHz UWB channels [5]–[7] and 60-GHz networks [8], [9]. The most comprehensive contribution is the development of the IEEE 802.15.4a standardized UWB channel model [7], which compiled models characterizing indoor residential, indoor office, outdoor, agricultural, industrial, and body-area environments. Despite the large quantity of these descriptive channel models, no existing effort applies to the environment within a computer system. For example, parameters describing the path loss and channel impulse response (CIR) of this channel are expected to differ significantly from those of common indoor channels because of the small size, dense multipath, and fully enclosed environment.

We present a measurement-based, statistical channel model for line-of-sight (LOS) UWB communications within a typical computer chassis. Channel parameters are derived by implementing best-fit algorithms on data obtained via the frequency-domain channel sounding approach [10], where a vector network analyzer (VNA) is used to obtain the scattering parameters of the channel. Hermitian signal processing [10] is utilized.
to find a close approximation of the CIR, based on the windowed frequency-domain transfer function output from the VNA. The basis of this proposed model is an adaptation of the 802.15.4a channel model that accounts for the differences between near-field and far-field propagation. Note that while the chassis has been characterized based on LOS measurements, the differences between the LOS and non-LOS (NLOS) scenarios have been found to be negligible due to the short propagation distances and metallic enclosure. Finally, an Intel blade server (3.33 GHz, quad-core) with chassis was programmed to stress all resources simultaneously, flooding the environment with the maximum radiated interference (worst-case interference scenario). A spectrum analyzer is used to evaluate the system-generated interference level in the 3.1–6-GHz frequency range.

II. CHARACTERIZATION OF THE CHASSIS

A. Propagation Path Loss

1) Measurement Setup: To determine the propagation path-loss parameters, measurements were taken at distances between 1–40 cm in increments of 1 cm within the chassis interior of a standard desktop workstation with dimensions 45×20×40 cm³. To accurately characterize the channel during normal operation, all miscellaneous components (hard disk drives, power cables, etc.) were left inside the computer during data acquisition. Measurements were taken inside a near-static, electromagnetically shielded lab. A VNA was used to capture 1601 data points between 3–6 GHz, providing a frequency-domain resolution of 1.875 MHz. Linearly polarized omnidirectional electric monopole antennas based on meander-line antenna technology, which are optimized for operation in the 3–6 GHz frequency range [11], were used in the measurement process. Specifically, the antennas are characterized by a peak gain and a minimum gain of 4.4 and −6.8 dBi, respectively, at 4.5 GHz in the azimuth cut and an average gain of approximately 0 dBi in the ϕ = 0º elevation cut between θ = 120º and 240º. The gain of the transmit and receive antennas and loss due to cables and connectors were calibrated and extracted in obtaining the channel path loss. Channel model parameters related to the propagation path loss are extracted using previously published methodologies [7], [12] and then applying best-fit algorithms on the measured data.

2) Model Parameterization: The propagation path loss of the channel is a function of both the distance between the transmitter and receiver, d, and the transmitted frequency f. This relationship is modeled as

\[ L(f, d) = L(f) \cdot L(d) \] (1)

where \( L(f) \) (\( L(f) \propto f^{-2\kappa} \)) is the frequency-dependent component and \( \kappa \) is the decay factor [7].

It is well known that the distance-dependent component \( L(d) \) in decibels can be piecewise-linear approximated with at least one breakpoint, depending on the ratio \( d \) and wavelength \( \lambda \). One breakpoint occurs at the transition point between near field and far field, which is generally near half the wavelength of the transmitted frequency [7]. This value for the in-chassis environment will be empirically determined from observations of the path-loss measurements. Multiple breakpoints might be needed to piecewise-linear approximate the path loss in the near-field region. For the electric field signal, the free-space propagation path gain (inverse of path loss) in the near-field region is proportional to

\[ \frac{1}{(\frac{2\pi d}{\lambda})^2} = \frac{1}{(\frac{2\pi d}{\lambda})^4} + \frac{1}{(\frac{2\pi d}{\lambda})^6}. \] (2)

Assuming the distance satisfies \( d \geq 1 \) cm, which is the minimum distance for interchip wireless communications and a frequency of 4 GHz, calculation shows that the near-field path loss in decibels can be well approximated by a single linear curve. We therefore model the propagation path loss as

\[ L_{d\text{dB}}(d) = \begin{cases} L_{01} + 10n_1 \log_{10} \left( \frac{d}{d_{01}} \right) + S_1, & d_{01} < d \leq d_{02} \\ L_{02} + 10n_2 \log_{10} \left( \frac{d}{d_{02}} \right) + S_2, & d > d_{02} \end{cases} \] (3)

where when \( d_{01} < d \leq d_{02} \), propagation is a near-field scenario; when \( d > d_{02} \), propagation is far-field. \( L_{01} \) is the loss at the reference distance \( d_{01} \). \( L_{02} \) represents the path loss at the transition distance \( d_{02} \), \( n_1 \) and \( n_2 \) are the near-field and far-field path-loss exponents, respectively, and \( S_1 \) and \( S_2 \) are the zero-mean Gaussian-distributed near-field and far-field shadowing components with corresponding standard deviations \( \sigma_{S1} \) and \( \sigma_{S2} \) (in decibels).

All parameters related to this model are given in Table I. For each parameter, spatial averaging was implemented [7] to remove the frequency dependence of the path loss, except for \( \kappa \). Averaging was performed by repeating the path-loss experiment for different transmitting antenna positions and averaging the acquired data at each spatial position.

3) Comparison With Models of Common Indoor Environments: As expected, the path-loss breakpoint model accurately fits the measurement data, as shown in Fig. 2. Specifically, considering the number of measurements, we can specify a 95% confidence level for intervals of ±0.4 and 2.0 dB for near-field and far-field scenarios, respectively. It is also observed that most of the channel parameters within this computing environment differ considerably from those for indoor, residential, or industrial short-range UWB communications environments [7]. Most notably, the path-loss exponent \( n_1 \) for far-field propagation is significantly lower than any previously reported in existing published data. As explained in Section I, this channel is mostly enclosed by electromagnetic (EM)-reflective materials. In such an environment, a large portion of the energy emitted is reflected back to the receiver, rather than continuing outward. This results in a reduction of the signal energy lost over distance that is greater than the general 1/r² factor. As expected, the near-field path-loss exponent \( n_2 \) is much higher than for far-field, matching the wave theory presented in [7].
is the cluster index, \( k \) denotes the \( k \)-th ray of the \( I \)-th cluster, \( \beta_{k,i} \) denotes the path loss of the \( k \)-th path of the \( I \)-th cluster, \( \tau_{k,i} \) is the delay of the \( k \)-th path of the \( I \)-th cluster relative to the \( I \)-th cluster arrival \( T_I \), and \( \theta_{k,i} \) is the component phase, which is uniformly distributed over \([0, 2\pi]\). Through our experimental measurements, we have found that this expression adequately describes multipath propagation within this enclosed environment.

In a common indoor channel, the number of clusters \( L \) is generally modeled as a Poisson-distributed random variable \([7]\) with mean \( \bar{L} \). The probability density function (pdf) of \( L \) is expressed as

\[
    f_L(l) = \frac{\bar{L}^l e^{-\bar{L}}}{l!}.
\]

Clusters are typically identified by visual inspection \([7]\), while the mean \( \bar{L} \) is derived by averaging the observed clusters per impulse response.

Cluster interarrival times are exponentially distributed with cluster arrival rate \( \Lambda \) \([13]\). Because the modeled environment is expected to have dense multipath components, ray arrivals cannot be distinguished with the available resolution, and therefore we are unable to characterize ray-arrival-rate parameters \( \lambda_1, \lambda_2, \) and \( \beta \). A regularly spaced, tapped delay model \([7]\) is used for ray arrivals. \( \Gamma \) is the intercluster decay time constant, \( \gamma \) is the intracluster decay time, and \( \sigma_{\text{cluster}} \) is the cluster-shadowing standard deviation \([13]\). These parameters were extracted as in \([7]\). We have also observed that the distribution of small-scale component weights \( \beta_{k,i} \) is Nakagami with a log-normal distributed \( m \)-factor. The parameters \( \mu_m \) and \( \sigma_m \) are the mean and deviation of the \( m \)-factor, respectively.

The rms delay spread \( \tau_{\text{rms}} \) used to interpret delay dispersion, is another useful quantity when observing a channel. While this parameter has been found to vary with distance \([7]\), because the maximum transmission distance for our channel environment is so short, we have found that a mean value \( E\{\tau_{\text{rms}}\} \) is sufficient to characterize this factor. All parameters related to the channel impulse response model are derived from best-fit algorithms on the measurement data \([7], [14]\) and are provided in Table II.

### 3) Comparison to Models of Common Indoor Environments:
Here, we note additional dissimilarities between our model and those already in existence \([7]\). From Table II, the intercluster decay constant \( \Gamma \) is significantly lower than that presented in \([13]\), despite accurate modeling (Fig. 4). Recall from Section I the special properties of this channel, where reflectivity is fairly uniform across the entire enclosure. This indicates that the average power of each multipath component will monotonically decrease. Because a large proportional

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**Table II**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Near-Field</th>
<th>Far-Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L ) (cm)</td>
<td>1 to 3</td>
<td>3 to 40</td>
</tr>
<tr>
<td>( \Lambda ) (1/( \mu ))</td>
<td>0.277</td>
<td>0.376</td>
</tr>
<tr>
<td>( \Gamma ) (( \mu ))</td>
<td>17.13</td>
<td>23.03</td>
</tr>
<tr>
<td>( \gamma ) (( \mu ))</td>
<td>1.12</td>
<td>1.03</td>
</tr>
<tr>
<td>( \sigma_{\text{cluster}} ) (( \mu ))</td>
<td>5.55</td>
<td>3.87</td>
</tr>
<tr>
<td>( \mu_m ) (( \mu ))</td>
<td>1.57</td>
<td>1.76</td>
</tr>
<tr>
<td>( \sigma_m ) (( \mu ))</td>
<td>1.04</td>
<td>0.99</td>
</tr>
<tr>
<td>( E{\tau_{\text{rms}}} ) (( \mu ))</td>
<td>25.65</td>
<td>23.62</td>
</tr>
</tbody>
</table>

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**Fig. 2** Propagation path-loss model versus measurement data.

**Fig. 3** CIR measurement setup.

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### B. Channel Impulse Response

#### 1) Measurement Setup: The measurement setup for the channel impulse response model is shown in Fig. 3. For this unique environment, we have chosen an antenna positioning approach different from the conventional methodology \([6]\). By measuring along segments of radial lines rather than along a grid, we have eliminated the propensity for time-shifting of clusters due to distance variations between the transmitting and receiving antennas. Additionally, we have found that this approach reduces amplitude distortion due to shadowing. Finally, we adopted the frequency-domain channel sounding method as described in \([10]\), using Hermitian signal processing to derive the CIR.

#### 2) Model Parameterization: According to the Saleh–Valenzuela model \([13]\) for indoor propagation, the complex baseband impulse response for a general indoor multipath propagation can be expressed as

\[
    h(t) = \sum_{k,i} \beta_{k,i} e^{j\theta_{k,i}} \delta(t - T_i - \tau_{k,i})
\]

where \( I \) is the cluster index, \( k \) denotes the \( k \)-th ray of the \( I \)-th cluster, \( \beta_{k,i} \) denotes the path loss of the \( k \)-th path of the \( I \)-th cluster, \( \tau_{k,i} \) is the delay of the \( k \)-th path of the \( I \)-th cluster relative to the \( I \)-th cluster arrival \( T_I \), and \( \theta_{k,i} \) is the component phase.
amount of the signal energy is lost in the near field, cluster power will decay much faster than in open environments, as observed in (1) with values from Table I. It is important to note that the average number of clusters $\bar{L}$ is much higher in this environment than that of existing UWB channel models [7]. Fig. 4 illustrates the high density of multipath clusters (MPCs) encountered in this environment due to the reflectivity of the metallic surroundings. Because the area of the computer chassis is small, electromagnetic waves are reflected without losing much of their energy, such that strong clusters will appear multiple times in the CIR. This property can be exploited to overcome difficulties arising from NLOS communications.

Note that the 802.15.4a standard channel model for UWB communications ignores the effects of the radiation system. There is a strong correlation between antenna beamwidth and rms delay spread for directional antennas [15]. It has also been shown that real UWB antennas will not provide true omnidirectional performance [16]. Finally, it has been demonstrated that the UWB antenna chosen for a system greatly affects the propagation characteristics of the transmitted pulse [16]. Therefore, the 802.15.4a standard provides channel modeling information that, while sufficient for standard implementations, is insufficient for practical applications in more complex communication environments.

III. CHANNEL INTERFERENCE CHARACTERIZATION

The interference caused by the switching noise of the different ICs on the motherboard can limit the maximum channel data rate. In order to understand the characteristics of the channel completely, electromagnetic interference (EMI) is characterized inside the computing enclosure. A test suite was custom-designed to generate the maximum switching-noise interference by enabling all resources on the motherboard to be concurrently switching. From this analysis, the highest INR levels within UWB frequencies were at 3.14, 3.44, and 5.73 GHz at 21.8, 20.0, and 25.9 dB, respectively, with the microprocessor clock running at 3.33 GHz. These variations in the INR at different frequencies indicate that fine-tuning of the transceiver’s operating frequency can significantly improve the error performance. It is interesting to note that the CPU clock, which was expected to be the strongest interference source, does not appear as a peak in this analysis.

REFERENCES