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Worse-than-Rayleigh Fading: Experimental Results and Theoretical Models

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ABSTRACT

This article is motivated by the recent recognition that channel fading for new wireless applications is not always well described by traditional models used for mobile communication systems. In particular, fading data collected for vehicle-to-vehicle and wireless sensor network applications has motivated new models for conditions in which channel fading statistics can be worse than Rayleigh. We review the use of statistical channel models, describe our example applications, and provide both measured and modeling results for these severe fading conditions.

INTRODUCTION

To put these severe fading conditions in context, we first briefly discuss the importance of channel modeling in wireless communication systems. As a frame of reference for our modeling results, we review the assumptions and statistics for the classical Rayleigh fading model. This statistical model has long been used as a worst case condition for mobile communication systems, but as we show, it is not always conservative enough for a number of important applications.

IMPORTANCE OF CHANNEL MODELING

The importance of accurately modeling the effects of wireless channels on communication signals is well established [1]. This includes modeling the effects of propagation path loss, or attenuation, for the determination of link budget parameters such as required transmitter power, achievable link distance, and receiver sensitivity. In addition to estimating path loss vs. distance, the *variation* of this propagation path loss over large areas, typically tens to hundreds of wavelengths, is also useful to model. This variation is often termed "large-scale" fading, and in built-up areas is also known as shadowing or obstruction.

A separate and largely independent channel effect is the phenomenon of "small-scale" fading. This type of fading occurs on spatial scales on the order of one-half wavelength. Small-scale fading, in most settings, is a direct result of the constructive and destructive addition of multiple delayed replicas of the transmitted signal as seen at the communications receiver. These multiple replicas travel different path lengths and have different amplitudes and phases, resulting in a phenomenon known as multipath fading. Modeling such small-scale fading is important in physical layer (PHY) design, as it helps engineers design fading countermeasures, such as diversity transmission/reception, forward error correction coding and interleaving, and equalization. In this article we focus attention on small-scale fading, with a brief mention of some "medium-scale" or "meso-scale" effects.

Since the PHY forms the foundation of the communications protocol stack, the transmission performance of this layer — often measured in terms of bit error ratio (BER), or packet error ratio (PER) — affects all higher layers of the stack. Some current research (e.g., [2]) has also begun to "extrapolate" the PHY channel effects on transmission performance to higher layers for a more integrated approach to system modeling; this approach is related to the current topic of cross-layer design.

Modern wireless communication systems are highly complex. Even at the physical layer, many new systems, such as wireless local area networks (WLANs), provide a range of transmission and reception options. These options are almost always adaptively employed, and enable the system to operate in a range of channel conditions, with different numbers of system users, different data rates, and different transmission qualities (so-called quality of service, QoS). Yet even with such highly reconfigurable systems, the impairments caused by the channel may be severe enough to degrade performance significantly if the channel characteristics are not taken into account in advance. Such performance degradations could include a BER/PER "floor," wherein the error probability reaches a lower limit regardless of received power level, and a large latency (delay). For some protocols this large latency can translate to a link outage and/or multiple retransmissions.

Statistical models are most often employed for characterizing small-scale fading effects. These statistical models do not aim to accurately predict fading at any given point in time and space, but rather attempt to faithfully reproduce the variation of channel effects. Deterministic models (e.g., ray tracing) can also be used, yet to be accurate, deterministic modeling tends to require much more computation and a substantial amount of data on the local environment, particularly when channel mobility is high. Thus, these models are less "portable" and are often "site specific."

A FRAME OF REFERENCE: RAYLEIGH FADING

A fairly general expression for the received signal in a multipath environment is the Two-Wave, Diffuse-Power (TWDP) model [3]. As illustrated in Eq. 1, the received signal voltage, $V_{received}$, is dependent on two specular signal paths (V_1 and V_2) along with $L - 2$ diffuse (i.e., scattered) lower-amplitude components. The specular components are those of significant magnitude; for example, they may be line of sight (LOS) components.

$$V_{received} = V_1 \exp(j\phi_l)$$
$$+ V_2 \exp(j\phi_2) + \underbrace{\sum_{i=3}^{L} V_i \exp(j\phi_i)}_{\text{diffuse component}} \quad (1)$$

The case without specular components (i.e., $V_1 = V_2 = 0$) is commonly assumed in mobile systems where an LOS component may not be guaranteed. When L is large there are many reflected components, and the diffuse component of Eq. 1 will be complex with the real and imaginary components well modeled as independent and identically distributed (i.i.d.). For large enough L, by the central limit theorem these real and imaginary components are approximated as zero-mean Gaussian random variables with standard deviation σ. It is well known that the resulting summation of these components has an envelope, $r = |V_{received}|$, with Rayleigh statistics [1]. That is, the probability density function (pdf) for the received envelope r is, for $r \geq 0$,

$$f_r(r) = \frac{r}{\sigma^2} \exp[-r^2/(2\sigma^2)] \quad (2)$$

For mobile systems, the Rayleigh fading assumption is a common "default" for worst case performance analyses. Integrating the pdf in Eq. 2 from 0 to r results in the cumulative distribution function (cdf), commonly plotted on a log-log scale as in Fig. 1. The cdf is a useful representation for fading phenomena, for we can utilize the curve to ascertain the probability of a particular fade depth. For example, we see from Fig. 1 that for a Rayleigh channel, the probability of a 20 dB fade relative to the median received power is 1 percent. Thus a system designer can assure 99 percent link reliability in this environment if 20 dB of margin is provided. For environments where there exists a single specular component (e.g., LOS), we have $V_2 = 0$ in Eq. 1. In this case, described by the Ricean distribu-
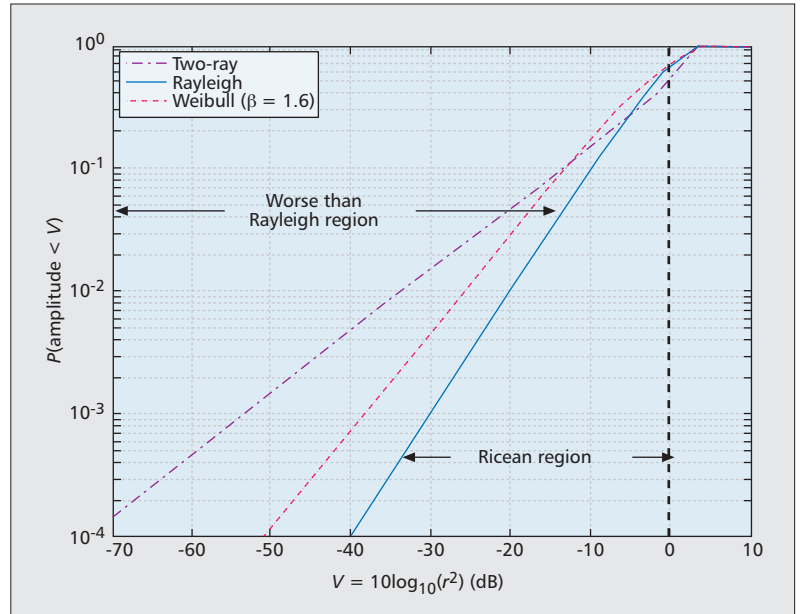

Figure 1. *Cumulative distribution functions (cdf) for Rayleigh, Weibull ($\beta = 1.6$), and two-ray fading. The region more benign than Rayleigh is indicated as Ricean.*

tion, the fading becomes more benign since the specular components can no longer cancel each other. In the cdf plot of Fig. 1, we see the Ricean region lies below the Rayleigh curve, indicating lower probabilities of severe fades.

The Ricean and Rayleigh distributions are well discussed in the literature and ubiquitously used in practice [1]. In this article, however, we focus our interest on fading phenomena whose cdf curves lie above the Rayleigh curve; that is, the fading is *worse than Rayleigh* or, synonymously, severe. This is also indicated in Fig. 1 by the Weibull and two-ray cdfs, which we describe and employ subsequently.

CHANNEL MODELING FOR EMERGING APPLICATIONS

Wireless communications is being used in an expanding variety of applications and in new ways. In the traditional mobile setting, connections to the network often persist for long time periods, as users more frequently desire an "always on" status for their devices. This translates into wider areas of service, which can mean a wider variety of environment types, including within vehicles or pedestrian, in urban, suburban, and rural settings, both indoor and outdoor. Thus, long-term/wide-area channel models are needed for these conditions. Long-term modeling implies an abandonment of the typical wide-sense stationary, uncorrelated scattering (WSSUS) channel assumptions long used by researchers and system designers since the channel statistics will change when observed over a long enough time period and/or a wide enough area. Thus, non-stationary (NS) modeling techniques may be required to faithfully represent channel fading. Similarly, operation in new environments may yield different fading characteristics [4].
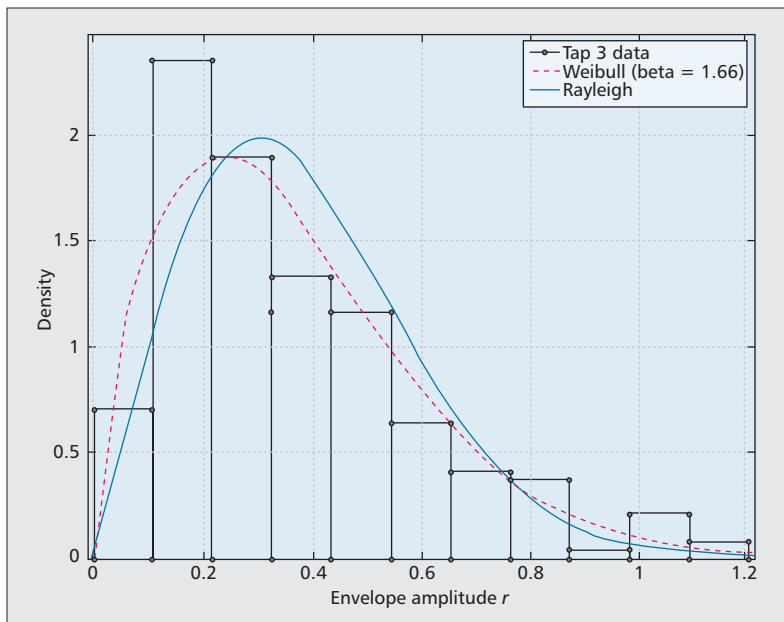
Figure 2. *Measured multipath component amplitude histogram and two pdf fits, Rayleigh and Weibull (β = 1.66) [6].*

Historically, fading that does not follow the classical Rayleigh or Ricean distributions has been reported in many environments. This includes severe fading in forests, urban and sub-urban cellular settings, and indoor environments; see [5] for an overview discussion of the literature on severe fading. Hence, although Rayleigh and Ricean models have been well utilized for mobile communication systems, emerging applications may not be well served by these classical distributions [6].

In particular, our interest in modeling severe channel fading comes from experience with two such emerging wireless applications, vehicle-to-vehicle (V2V) communications and wireless sensor networks (WSNs). It is fair to say that additional unforeseen wireless applications will emerge in coming years. As has been true in the past, the availability of accurate channel models for these applications will continue to be vital for efficient and high-performance systems.

Vehicle to Vehicle (V2V) — The V2V channel differs from the conventional mobile (cellular) channel in several ways. First, both platforms (transmitter and receiver) are mobile, which can cause fading dynamics to be more rapid than in the cellular case. Second, antenna heights are low for both platforms, and this can not only obstruct the radio LOS, but also cause scattering from a greater number of objects in the local environment. In many V2V settings, isotropic scattering will be rare, and WSS conditions will pertain for a generally shorter time period than in conventional cases.

Vehicles in V2V settings essentially form large mobile scatterers, and rapid movements can cause abrupt changes in multipath channel conditions. This effect can be viewed as a medium- or meso-scale effect, between that of the large-scale shadowing attributable to buildings and the small-scale fading due to destructive addition of multipath components. If these abrupt changes or "transition effects" are rapid enough, severe fading can result, as we describe subsequently. This model will not generally fit that described in Eq. 1.

A standard for V2V communication currently exists for the 5.9 GHz unlicensed national information infrastructure (UNII) band, the dedicated short-range communication (DSRC) standard. This is essentially an extension of the IEEE 802.11a WLAN standard. As with most WLAN standards, the DSRC standard specifies the transmission scheme at the lower two layers of the communications protocol stack. For any applications regarding safety, extremely high reliability is essential. For most currently envisioned V2V applications, data rates are modest, but as new V2V applications arise, required data rates may increase, and newer standards may be needed to support these applications (e.g., extended versions of the IEEE 802.16e wireless metropolitan area network [WMAN] standard, WiMAX). Some potential advantages of 802.16e over the modified 802.11a standard in V2V environments are its higher data rate, fast feedback channel for mitigating fading, and stronger forward error correction (FEC) coding for better performance. Whatever the transmission scheme employed, knowledge of the wireless channel is vital to the optimal design and performance of any V2V communication system.

Wireless Sensor Networks — In comparison to cellular communication systems or V2V systems, wireless sensor deployments are unique due to their location, for example, near-ground, underground, at air/water boundaries, or embedded in composite structures. They are also typically static (non-mobile) in nature. As such, current propagation and temporal fading models for mobile systems (e.g., Rayleigh and Ricean) may not necessarily be applicable. In particular, although the time variability in a WSN channel may be inconsequential, one may certainly expect signal variability over small changes in mounting location or in frequency of operation due to the multipath environment. That is, the channel will still be frequency-selective and/or spatially selective due to the multipath environment.

To date, short link distances and poor link reliability have plagued WSN deployments. In addition, little channel research has been conducted for this application space, and often only simplistic large-scale (path loss) models are considered (e.g., plane-earth). This dearth of work is especially serious due to the energy-constrained nature of wireless sensors (i.e., the need to minimize transmission power) and the desire to have high-quality links (i.e., to minimize packet retransmissions).

RECENT WORK ON SEVERE FADING WIRELESS CHANNELS

MEASUREMENTS

V2V — A number of measurement and modeling campaigns for V2V channels have been recently conducted [6–8]. The authors of [7] developed channel models for several V2V set-

tings based on measurements taken in the 5 GHz band. Settings included both urban and highway, with varying link distances and velocities. Their results for measured Doppler spectra showed significant variation over time, indicating statistically non-stationary fading. Amplitude fading was modeled as either Rayleigh or Ricean for convenience, since the V2V models developed were aimed at implementation on a hardware channel emulator whose library of statistical models was limited. The authors of [8] measured and modeled large-scale path loss and flat fading in suburban Pittsburgh, and also found some severe fading.

Figure 2 shows a histogram of measured fading amplitude data taken in V2V measurements in a small city [6]. In our measurements, we used a 50 MHz bandwidth spread spectrum stepped correlator in the 5 GHz band. The unambiguous delay range was 5 μs. Antennas were mounted on vehicle roofs (except for one model class for which antennas were inside the vehicles), and the vehicles moved throughout several environments: large cities, small cities, and highways in Ohio. The vehicle velocities were up to 10 m/s in cities, with intervehicle distances from a few meters to approximately 100 m. Both heavy and light vehicle traffic were encountered, with occasional blockage of the LOS signal by large vehicles, and by buildings when the leading vehicle turned a corner. City areas traversed were those with tall buildings (4–5 stories for the small cities, more than 10 stories for the large cities) on both sides of the street. The highway velocities were approximately 26 m/s, with relative velocities between the vehicles substantially less. Highway intervehicle distances were up to approximately 1 km, but most data was collected with intervehicle distances between a few tens to several hundred meters. In all environments, measurements were taken with the receiver vehicle both in front of and behind the transmitter vehicle. The histogram in Fig. 2 is an "empirical pdf" for the amplitude data of the third multipath component in a channel model of bandwidth 10 MHz. Two fits employing analytical pdfs — the Rayleigh and Weibull densities — are also shown. Since the pdf is the derivative of the cdf, the fading probability $P[r < r_0]$, for some level r_0 can be computed as the amount of area under the pdf curve from zero to r_0. As can be seen, the Weibull pdf has more area at low values of amplitude than the Rayleigh, indicating a greater likelihood of severe fading for this multipath environment. We describe the Weibull pdf in the next section on modeling.

WSN Deployments in Enclosed Environments — As noted, many sensor networks are envisioned to utilize nodes that are statically deployed, often on or within the environment being monitored. One application space being explored is the use of such sensing devices within and about cavity structures such as aircraft, other vehicles, and shipping containers. Such sensing systems could improve predictive maintenance and security efforts, for example. These structures are typically metallic and thus ideal environments for creating multiple strong signal paths. The constructive and destructive combin-
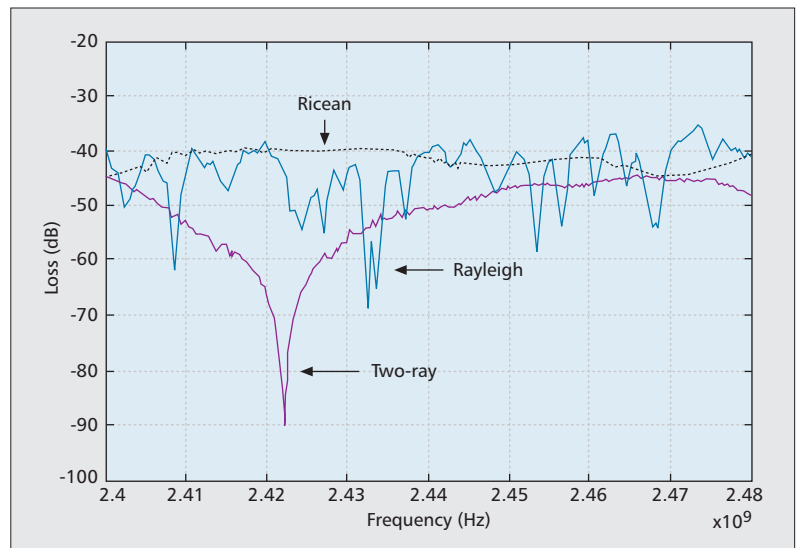

Figure 3. *Frequency-selective fading response as a function of cavity configuration [9].*

ing of the multipath signals are strongly dependent on small changes in the:
• Configuration of the environment
• Location of the wireless devices
• Frequency of operation

To illustrate the sensitivity to small-scale changes, Fig. 3 shows the multipath impact measured within a cavity structure [9]. This data was collected using a vector network analyzer to measure the frequency response (S_{21}) across the 2.4 GHz industrial, scientific, and medical (ISM) band between two antennas located within the cavity. In this plot, the different curves represent slightly different positioning of the antennas within the space. Clearly, both position and frequency of operation determine the received signal strength and therefore communication link reliability. Analyzing link reliability or establishing communication link margins without appropriate models for such small-scale effects is likely to yield systems that underperform. As such, we now consider models for the severe fading conditions described.

MODELING SEVERE FADING

Multiple Scattering — Multiple scattering produces fading that, in contrast to the additive expression of Eq. 1, can be represented by more than one *multiplicative* process [6]. In this case, several small-scale fading processes are multiplied together, resulting in a new product process with worse than Rayleigh statistics. This has been used for modeling the V2V channel where both transmitter and receiver can be modeled as being surrounded by a "ring" of scatterers [9, references therein]. Similarly, this has been used for the so-called "keyhole" and "pinhole" channels in multi-antenna or multiple-input multiple-output (MIMO) channels [6]. When the number of processes multiplied together to form the composite fading amplitude is two, the models are often called "double" (e.g., two Rayleighs multiplied together yields a "double Rayleigh" channel). We have also developed a double Weibull model [6], and other authors have gen-

Measurement set	Good state time percentage T_g	Good state Weibull (α, β)	Bad state time percentage T_b	Bad state Weibull (α, β)	Single state Weibull (α, β)
V2V$_1$	46	(0.89, 2.7)	54	(0.43, 1.87)	(0.64, 1.77)
V2V$_2$	52	(0.78, 2.6)	48	(0.32, 1.87)	(0.56, 1.64)

Table 1. *Weibull distribution parameters for channel transition severe fading models [5].*
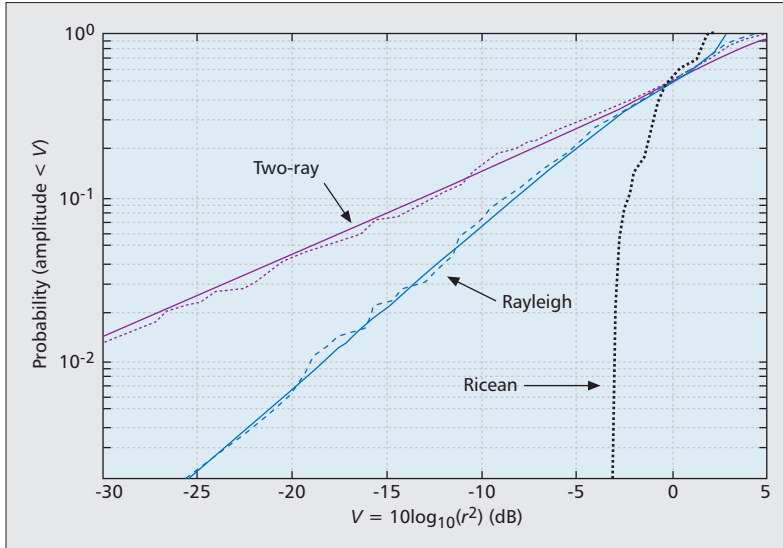
Figure 4. *Cumulative distribution function (cdf) for fading data of Fig. 3, along with theoretical Rayleigh and two-ray model curves [9].*

eralized to more than two processes. Generally, if any one process is Rayleigh or worse, the resultant product will be severe fading. In these multiplicative models, it is simplest in the end to model the composite (product) process via a *single* severe fading process. Several authors have done this (again, see [6]) and many have found the Weibull density to be appropriately flexible for this fitting task.

In [6] the authors reported severe fading in multiple V2V settings, also based upon measurements in the 5 GHz band. The empirical models in [6] employ the Weibull fading distribution to approximate measured severe fading conditions:

$$f_W(r) = \frac{\beta}{\alpha^\beta} r^{\beta-1} \exp\left[-\left(\frac{r}{\alpha}\right)^\beta\right] \qquad (3)$$

where parameter β, the shape parameter, controls the severity of fading (and is analogous to the Ricean K-factor), and parameter α, the scale parameter, controls the mean-square value. Specifically,

$$\alpha = \sqrt{\Omega / \Gamma[1 + (2/\beta)]}, \text{ with } \Omega = E(r^2),$$

with E denoting expected value and Γ the gamma function. When $\beta = 2$, the Weibull distribution is equivalent to the Rayleigh, and for $\beta > 2$, the distribution is analogous to the Ricean. Values of $\beta < 2$ model severe fading. The Weibull distribution was selected in [6] via a maximum likelihood criterion, and fit better than other standard distributions (e.g., Nakagami). Figure 1

shows the Weibull cdf for $\beta = 1.6$, a value obtained for some V2V channel model coefficients in [6]. Values of β in the V2V measurements ranged from 2.4 to 5.1 for the first-arriving multipath component, and from 1.6 to 2 for components at larger values of delay. References within both [5, 6] list other works in which the Weibull distribution has been used to model amplitude fading.

Channel Transitions — The second model for severe fading that we discuss is similar in principle to models developed for the land mobile satellite channel. In this case, as a receiver moves between different fading environments (e.g., from LOS to non-LOS [NLOS]), the envelope power distribution changes. This change of received power (transition) is typically from shadowing or large-scale fading, but if the changes occur rapidly enough, as can happen in V2V environments with medium-scale vehicular obstructions, the result can be severe fading. In the satellite channel case, these two conditions are denoted as channel states.

These transitions are also often accompanied by a "redistribution" of power among the multipath components. This is most easily explained via the LOS to NLOS transition case, where if the LOS component is rapidly attenuated and the NLOS components are not, the power delay profile can change significantly. The power delay profile is often quantified using the root mean square delay spread (RMS-DS) [1]; less dispersive (e.g., LOS) channels generally have lower values of RMS-DS than do highly dispersive (e.g., NLOS) channels. We can model these small RMS-DS conditions as "good" states, and the large RMS-DS conditions as "bad" channel states. In some of our measurements in V2V settings [5], we have observed severe fading where we encounter transitions between these two states. The rows of Table 1 show example Weibull amplitude statistics from two V2V measurement sets. The table also lists statistics on the percentage of time T_{state} ($state = good$ [g] or bad [b]) the channel spends in each state. The third and fifth columns provide Weibull fit parameters for data in each state separately. For these cases, the "bad" state is very close to Rayleigh (β close to 2), and the "good" states have a larger β factor. When we combine the data from both states and create a single pdf model (just as is often done for multiplicative fading), severe fading behavior is evident from the resulting β factors (< 2). We have also corroborated this measured effect in computer simulations.

Two-Ray Model for Static WSN Deployments — As noted earlier in our discussion of the TWDP model and expression (1), it is well known that Rayleigh fading arises from the summation of a large number of uncorrelated roughly equal-amplitude multipath components. Yet if the number of multipath components becomes small, the central limit theorem is no longer valid; hence, the real and imaginary components of the received signal will no longer be Gaussian distributed. Consequently, the envelope fading statistics will no longer be Rayleigh. In [4] the author covered a limiting case of this condition in which only the two specular components (V_1 and V_2) found in Eq. 1 were considered. This condition may arise in communication links within metallic cavity structures. When the two components are of equal weight ($V_1 = V_2$) and add with phase uniformly distributed between 0 and 2π, the result is the two-ray small-scale model, which was shown to have the following probability density function for received envelope r:

$$f_{TR}(r) = \frac{2r}{\pi\sqrt{4r^2 - r^4}}, \text{ where } r \in (0,2). \qquad (4)$$

Although this result is theoretically interesting, it is worth recognizing that indeed such fading conditions can be found in practice. Reconsider the data presented in Fig. 3. Plotting the cdf for the fading response in Fig. 4, we find that these three data sets — which again were collected in the same cavity environment but under slightly different configurations — exhibit a broad range of fading conditions. In our channel measurements conducted aboard airframes in the 2.4 and 5 GHz ISM bands [10], it was not uncommon (~20 percent of the time) for the channel cdf curves to lie between the Rayleigh and two-ray models (i.e., in the worse than Rayleigh or severe fading region).

Impact of Severe Fading on System Performance — Finally, in Fig. 5 we show some example bit error probability results to illustrate the effects of severe fading on this performance measure. Modulation is coherent binary phase shift keying (BPSK), and average bit error ratio is plotted vs. energy-per-bit-to-noise-density ratio E_b/N_0 in dB. The curves shown are for four different channels: the additive white Gaussian noise (AWGN) non-fading channel, the classical Rayleigh fading channel, a Weibull fading channel with scale factor $\beta = 1.6$, and the two-ray channel. As can be seen, for the two severe fading distributions, error probability is significantly larger than that for the Rayleigh case. On this scale, the Rayleigh plot is said to have a slope of one — P_b drops by one order of magnitude for every 10 dB increase in E_b/N_0. The Weibull plot has both a smaller slope (~0.75) than the Rayleigh and a slight rightward shift. The most severe two-ray case has a slope of 0.5. Severe fading has similar effects on other transmission schemes.

SUMMARY AND CONCLUSIONS

In this article, we provide examples of emerging wireless communication systems for which common small-scale fading models may not adequately describe the channel's fading severity. In
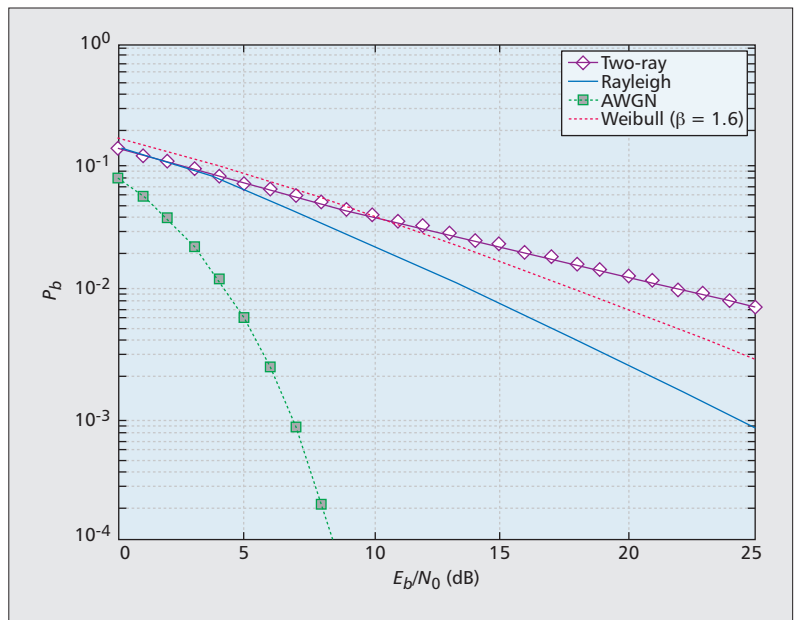
Figure 5. *Bit error probability vs.* E_b/N_0 *(dB) for coherent BPSK under various channel conditions: AWGN, Rayleigh, Weibull (β = 1.6), and the proposed worst case for sensor nodes, two-ray.*

particular, we have focused on empirical results and new models targeted to dynamic V2V and static WSN systems — applications in which fading has been recently demonstrated to be worse than Rayleigh. Multiple explanations for severe fading, including the two-ray model, multiplicative scattering, and channel transitions, were provided to support measured findings. Results to date indicate that new models for these severe fading phenomena still require refinement for the purpose of understanding and improving the link reliability in these systems. Some of these refinements include developing a plausible theoretical explanation for Weibull fading, beyond its empirical basis, and further specification of the transition model parameters for severe fading. For many static wireless sensor deployments, the use of the two-ray model may yield a too-conservative design. As such, the development of a parametric model for severe fading (something akin to the *K*-factor in Ricean fading) would be of benefit. Thus, we hope this article motivates other researchers to pursue future research in this area.

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BIOGRAPHIES

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