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A Simulation Method for Bit-Error-Rate-Performance Estimation for Arbitrary Angle of Arrival Channel Models

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Abstract

In this paper, a model for performing bit-error-rate (BER) analysis of various channel models is presented. Traditional simulation methods model the mobile radio channel as having Rayleigh fading, and are focused on the fluctuation of the amplitude of the received signal. Modern spatial models include information such as the angle of arrival of the incoming signals, the time-delay spread, and the number of multipath components. A simulation tool is developed that exploits the spatial statistical characteristics of the channel in order to derive estimates of the expected BER performance. The specific case of the Geometrically Based Single-Bounce Elliptical Model (GBSBEM) is presented and compared to the Rayleigh model. The impact of the employment of antenna arrays at the receiver is also examined. The possibility of determining the BER performance of communication systems, assuming arbitrary channel models, is justified.

Keywords: Communications channels; fading channels; dispersive channels; interchannel interference; multipath channels; Rayleigh channels; Rayleigh distributions; error analysis; antenna arrays

1. Introduction

During the development of a communication system, the problem of evaluating its performance often appears. This need exists in early design stages, when one wants to rapidly compare the behavior of different candidate solutions. It also appears in later design stages, when a more accurate estimate of the system performance is required. In modern wireless communication systems, the impact of various transmitting and receiving techniques, as well as of different propagation environments, is progressively more and more difficult to evaluate. The traditional method of link-budget analysis is quite inaccurate, and the production of a single prototype may prove very costly if a failure occurs. The necessity for simulation techniques being able to predict critical system-performance measures, such as bit-error rate (BER), fading, availability, capacity, etc., is imperative. In this paper, a simulation tool developed with the aid of *MATLAB* is presented (the model presented herein is available to interested researchers via e-mail to smitil@mail.ntua.gr). An open architecture is used that allows various statistical characteristics of the channel to be altered, such as the amplitude of each multipath component, the number of paths, and the channel model itself. The transmitter and receiver may have either omnidirectional or directional antennas.

For simple communication systems, it may be possible to derive a closed-form expression for the bit-error probability (BEP), but in practical cases it is usually intractable. In most real-life cases, a more realistic approach of estimating the BER of the system using Monte Carlo (MC) simulations is adopted. This approach is straightforward and may be used in any case, including those cases where the full description of the system is unavailable or the system is nonlinear [1]. The Monte Carlo simulations may be employed with arbitrary models for the transmitter and the receiver, as well as for the radio channel. Channel modeling is an important issue for the design and analysis of mobile communication systems. A profound knowledge of the radio-channel characteristics and propagation phenomena is a prerequisite for the development of efficient wireless systems. As reported in [2], there are various channel models that describe channel characteristics, such as the received signal amplitude or the time-varying distribution and Doppler spectrum of the channel. Modern channel models provide information about the time-delay spread, the angle of arrival (AOA) of the received signal, antenna array geometries, and the number of multipath components.

In the last few years, the enormous impact of antenna array systems has led to promising techniques for interference cancellation, position location, and capacity improvement. The use of antenna arrays has made the knowledge of the spatial properties of the channel an irreplaceable tool for the engineer who wants to estimate the effect of arrays on the system performance.

The simulation tool presented in this paper performs Monte Carlo simulations of wireless systems. The fading characteristics of the Rayleigh channel are taken into account, implementing a straightforward flat-fading generator function. The performance of the channel is estimated, and is found to be in agreement with the closed-form expression for the BER of a flat-fading channel and the results of recent work in the field. The approach proposed here explicitly uses the probability density function (PDF) of the angle of arrival to generate fading distributions and Doppler shifts. Thus, the probability density function of the angle of arrival of arbitrary channel models may be deployed in order to predict the specific BER of each channel. The probability density function of the angle of arrival for the Geometrically Based Single Bounce Elliptical Channel Model (GBSBEM), introduced in [3] and also presented in [4], is used, and results are obtained. The impact of antenna arrays is examined using an ideal directional receiver. For the GBSBEM model, the line-of-sight (LOS) component does always exist, and the array is assumed to always point in its direction. The receiver has a unity gain over ±20° around the line of sight, and zero gain elsewhere. The results show an explicit improvement of the BER when the array is used and the number of multipath components is small.

2. Theoretical Model

2.1 Rayleigh Fading Channel Model

The radio signals propagate in three dimensions in cellular radio systems. The forward link between the base station (BS) and the mobile station (MS) is considered herein. In this case, the base station is assumed to be over the rooftop, while the mobile station is assumed to be well below. With this assumption made, it is reasonable to suggest that the received field at the mobile station is made up of a number of horizontally traveling plane waves with vertical polarization [5]. The mobile station is moving with velocity v, while the nth incoming wave arrives with an angle ϕ_n. If the number of propagation paths is N, then the received bandpass signal is given by ([6])

$$r(t) = \mathrm{Re}\left[\sum_{n=1}^{N} C_n e^{j2\pi\left[\left(f_c + f_{D,n}\right)\left(t-\tau_v\right)\right]} \tilde{s}\left(t-\tau_n\right)\right], \qquad (1)$$

where C_n and τ_n are the amplitude and time delay associated with the nth path, respectively; f_c is the carrier frequency; $\tilde{s}(t)$ is the complex envelope of the transmitted signal; and $f_{D,n}$ is the Doppler shift, given by

$$f_{D,n} = f_m \cos\phi_n , \qquad (2)$$

where $f_m = v/\lambda_c$ and λ_c is the wavelength.

As presented in [5], in a simulation approach the statistical characteristics of the channel may be exploited, and the received signal may be expressed as a sum of many fewer multipath components, namely N_0, with N_0 given by

$$N_0 = \frac{1}{2}\left(\frac{N}{2} - 1\right). \qquad (3)$$

This approach has been followed in [7], giving a rapid and credible simulator. In this paper, a brute-force method has been followed, and the full number of multipath components in Equation (1) has been used. The number of paths necessary for simulation is justified to be $N \geq 26$ (see [5]). This number is selected herein to be $N = 50$. The angle of arrival is assumed to be uniformly distributed over $\left[0, 2\pi\right)$. The maximum Doppler shift is set equal to 160 Hz, corresponding to a reasonable outdoor mobile velocity of 20 m/sec if the carrier frequency is 2.4 GHz. The amplitude of each multipath component is assumed to be unity. In the case of Rayleigh fading, this results in a uniformly distributed received power respective to the angle of arrival, as proposed in [5]. In the case of the GBSBEM model, the unity-amplitude assumption results in a received power that is dense around the line of sight and sparse at the opposite direction. The fading is assumed to be flat, that is, only the amplitude of the signal envelope is affected. This assumption is valid if the differential path delays, $\tau_i - \tau_j$, are much smaller than the bit period, T_b, of the signal, and can be assumed approximately equal to $\hat{\tau}$. However, since the carrier frequency is very high, small differences in the path delay will still correspond to large differences in the received-signal phases [6]. Thus, the phase of the incoming signals is assumed to be uniformly distributed over $\left[0, 2\pi\right)$.

The approach followed herein is more time consuming than the classical approach presented in [5], but it has the significant benefit that it uses no statistical simplification of the channel. Thus, the simulator can accommodate channel models with arbitrary-angle-of-arrival probability density functions, corresponding to different propagation environments.

2.2 GBSBEM Channel Model

The GBSBEM channel model corresponds to indoor environments – including microcell and picocell systems – where base-station antennas are surrounded by clutter, and where scatterers are distributed between and around both the transmitter and the receiver. In this model, a line-of-sight component does always exist, while the scatterers are assumed to be uniformly distributed within an ellipse surrounding the transmitter and the receiver, and each path arrives at the receiver affected by only one single scattering. The locus of all points where a scatterer must lie in order to result in a single-bounce multipath component with delay τ_i is an ellipse with $a = c\tau_i/2$ and $f = d_0/2$, where d_0 is the transmitter-receiver separation. If the normalized path delay, $r_i = c\tau_i/d_0 = \tau_i/\tau_0$ is introduced, the conditional probability density function for the angle of arrival, ϕ, is given by ([4])

$$f_{\varphi|r_i} = \frac{\left(r_i^2-1\right)^{3/2}\left(r_i^2-2r_i\cos\phi+1\right)}{\pi\left(2r_i^2-1\right)\left(r_i-\cos\phi\right)^3}. \tag{4}$$

If it is assumed that only the scatterers positioned at distances corresponding to path delays lower than a maximum value, namely r_m, significantly affect the received signal, then the marginal distribution of the angle of arrival is given by

$$f_\phi(\phi) = \frac{1}{2\pi\beta}\frac{\left(r_m^2-1\right)^2}{\left(r_m-\cos\phi\right)^2}. \tag{5}$$

The value of r_m may be determined by taking into account signal components with a power level that is within a margin, T dB, of the direct path. Then, if the path-loss exponent is n and the reflection loss is L_r, the value of r_m may be calculated to be

$$r_m = 10^{\frac{T-L_r}{10n}}. \tag{6}$$

The probability density function given in Equation (5) is used to simulate a typical indoor environment suffering from flat fading. Samples of angle of arrival following this probability density function are generated and fed to the simulator. The number of multipath components is again assumed to be 50, the phase of the incoming waves is assumed to be uniformly distributed over $[0,2\pi)$, and the amplitude is unity for each propagation path. The maximum Doppler shift is set equal to 16 Hz, corresponding to a mobile velocity of 2 m/sec for a carrier frequency equal to 2.4 GHz, which is a reasonable value for an indoor environment.

A flow chart of the developed simulation tool is shown in Figure 1. A random digital data sequence is generated and the respective baseband analog signal is implemented. A large number of angles of arrival are generated (N in the figure), corresponding to the selected propagation model, and the flat-fading signal at the receiver is implemented. After additive white Gaussian noise (AWGN) is added, the BER is calculated. Rayleigh fading or the GBSBEM model may be selected, and different choices for the number of multipath components, N, can be made.

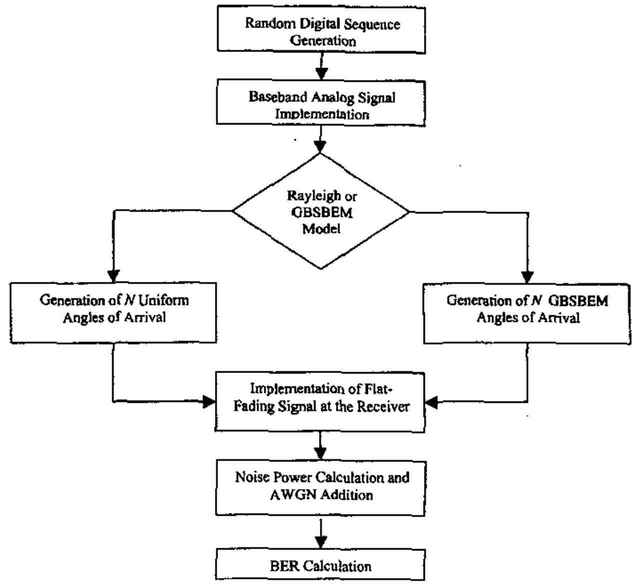

Figure 1. A flow chart of the proposed simulation tool.

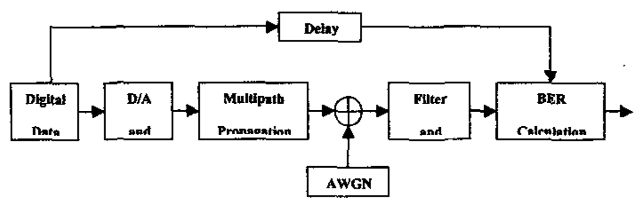

Figure 2. A block diagram of the system simulation approach.

3. Numerical Results

In all simulation scenarios, the simulator generated the low-pass equivalent of a BPSK signal of length equal to 65535 bits and of transmission rate equal to 100 kbps. The signal was over-sampled in such a way that eight samples of the signal were included within each bit period. A root Nyquist pulse-shaping filter was assumed at both the transmitter and the receiver. The pulse-shaped signal was transmitted over the radio channel. The multipath propagation was simulated by generating a great number of replicas of the signal (namely, 50), with different Doppler shifts and signal phases. The Doppler shifts arose from the corresponding angles of arrival, which followed either the uniform or the GBSBEM probability density function. The phase of each signal was uniform over $[0,2\pi)$. These replicas were summed, and the fading signal was created and normalized in order to have a mean power equal to unity. The fading signal was then multiplied by the transmitted signal to produce the corrupted received signal (flat-fading environment). The noise level was calculated at the receiver in order to perform BER measurements over discrete steps of the E_b/N_0 ratio from 0 dB to 10 dB. After additive white Gaussian noise was added according to the specified E_b/N_0, the received signal was passed to the sampler through the receiver's pulse-shaping filter. The received digital string was obtained via sampling of the received signal. The transmitted and received digital data were compared to each other, and the BER was calculated. The procedure was repeated 100 times for each E_b/N_0 ratio, and a mean BER value was obtained. A block diagram of the system-simulation approach is presented in Figure 2.

The impact of an antenna array on the system's performance was also extracted for the GBSBEM model. A perfect switched-beam array, always pointing in the line-of-sight direction, was

Table 1. The bit-error rate (BER) results for the Rayleigh-fading channel model.

E_b/N_0 (dB)	Proposed Simulator	Hiroshi-Harada Simulator [7]	Analytic Expression (Equation (7))
0	0.1445	0.1452	0.1464
1	0.1250	0.1248	0.1267
2	0.1070	0.1066	0.1085
3	0.0902	0.0905	0.0919
4	0.0759	0.0761	0.0771
5	0.0631	0.0625	0.0642
6	0.0517	0.0513	0.0530
7	0.0424	0.0425	0.0435
8	0.0347	0.0350	0.0355
9	0.0280	0.0282	0.0288
10	0.0226	0.0225	0.0233

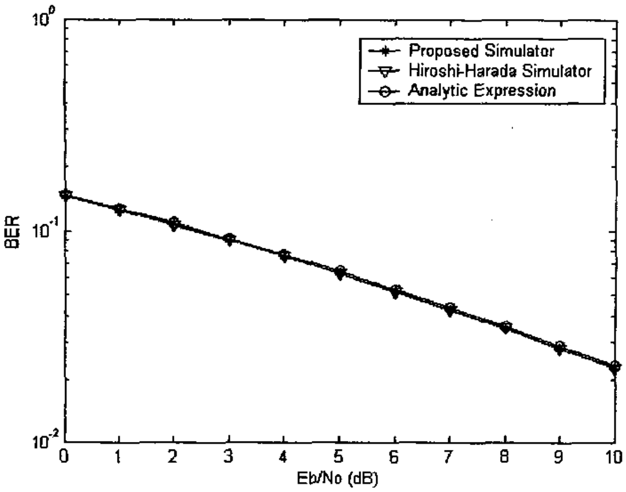

Figure 3. The bit-error rate (BER) as a function of the E_b/N_0 for the Rayleigh-fading channel model.

assumed. This perfect receiver exhibited a unity gain within ±20° of the line-of-sight direction, and zero gain elsewhere. Again, 50 incoming waves with random angles of arrival were generated, but in this case several of them were rejected by the array.

In the case of the Rayleigh fading channel, the simulation results are shown in Table 1, together with those from the simulator presented in [7]. In the same table, the results obtained from the analytic formula for flat-fading BER, given in Equation (7), are shown. In Figure 3, the results are depicted in a log-log scale diagram.

$$BER_{BPSK-FADING} = \frac{1}{2}\left[1-\left(\sqrt{1+\frac{1}{E_b/N_0}}\right)^{-1}\right]. \qquad (7)$$

Excellent agreement is shown between the proposed simulator and the analytic formula, which can be used for calibration purposes and verification of its reliability.

The same procedure was followed for the simulation of the GBSBEM channel model. In this case, the angle of arrival of each signal followed the probability density function given in Equation (5). The value of r_m was chosen to be 1.585, obtained from Equation (6) for a path-loss exponent of $n = 2$, a reflection loss of $L_r = 6$ dB, and a power margin of $T = 10$ dB. The simulated BER for an omnidirectional receiver and a perfect receiver is depicted in Table 2 and Figure 4. There is strong agreement between the performance of an omnidirectional receiver under the Rayleigh channel model and the GBSBEM model assumptions. This comes as a physical consequence if one considers the fading-generator model. The signals arrived from all possible directions. Thus, Doppler shifts were created and corrupted the received signal in a similar manner in both cases. The fact that in the GBSBEM case there was a higher density of multipath around the line of sight did not have an important impact on the BER, as long as significant multipath existed from the back and side angles, too. This was in contrast to the Ricean flat-fading channel model, where a discrete, strong line-of-sight component existed between the transmitter and the receiver. The simulated BERs were lower when the perfect receiver was used, as expected. The performance, although better, is not yet considered satisfactory, since a large number of incoming waves were detected, and the multipath fading was strong. Nevertheless, the capability of the simulator to treat cases with directional receivers was demonstrated.

Table 2. The bit-error rate (BER) results for the GBSBEM model.

E_b/N_0 (dB)	Omnidirectional Receiver	Perfect Directional Receiver
0	0.1437	0.1313
1	0.1247	0.1167
2	0.1070	0.0973
3	0.0892	0.0816
4	0.0751	0.0666
5	0.0631	0.0535
6	0.0511	0.0472
7	0.0425	0.0367
8	0.0346	0.0283
9	0.0278	0.0228
10	0.0226	0.0192

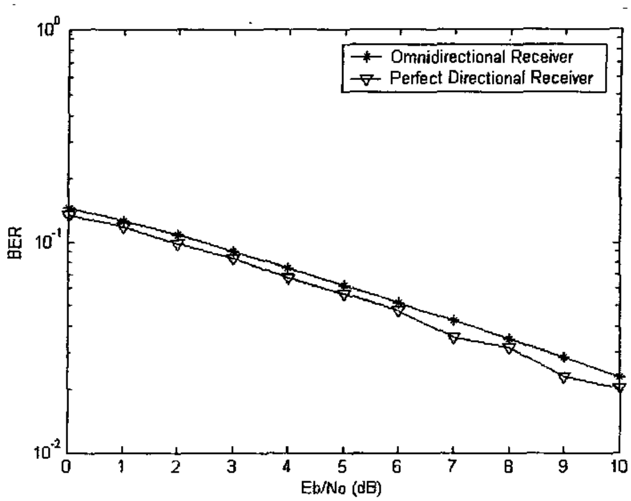

Figure 4. The bit-error rate (BER) as a function of the E_b/N_0 for the GBSBEM model.

Table 3. The bit-error rate (BER) results for the GBSBEM model with low multipath.

E_b/N_0 (dB)	Omnidirectional Receiver	Perfect Directional Receiver
0	0.1405	0.1177
1	0.1212	0.0978
2	0.1030	0.0782
3	0.0858	0.0648
4	0.0715	0.0516
5	0.0588	0.0422
6	0.0485	0.0360
7	0.0398	0.0263
8	0.0330	0.0233
9	0.0255	0.0208
10	0.0215	0.0152

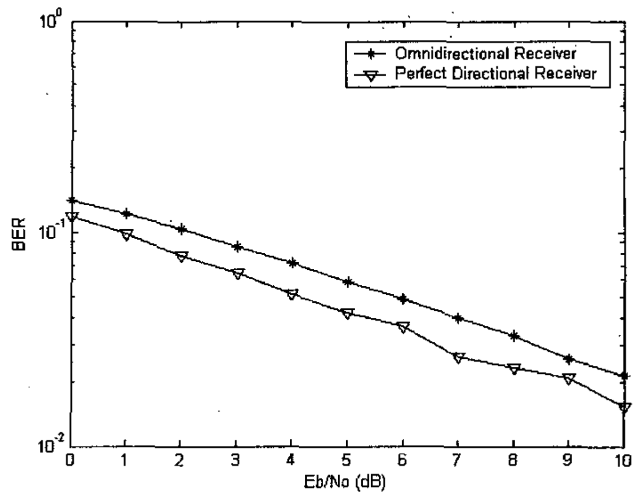

Figure 5. The bit-error rate (BER) as a function of the E_b/N_0 for GBSBEM model fore the case of low multipath.

The more realistic case of an indoor environment with a small number of significant multipath components arriving at the receiver is shown in Table 3 and Figure 5. It should be noted that when the number of incoming waves was small, no assumptions regarding the central-limit theorem could be made, and the sum of samples no longer followed the Gaussian distribution [8]. In this and other cases, there was no way to derive a closed-form expression for the BER of a system, and the Monte Carlo method had to be used. Only six incoming waves were assumed to arrive at the receiver from different angles, which followed the GBSBEM probability density function. The value of the maximum normalized delay was again set to $r_m = 1.585$. First, an omnidirectional receiver was used, and the BER was simulated. Then, the perfect ±20° receiver was used and simulated, with a line of sight always existing between the transmitter and the receiver, as imposed by the model. That is, in the cases where a line-of-sight component was not produced by the angle-of-arrival generator, it was added fictitiously. An explicit BER improvement of the link was noticed when the array receiver was used and the number of paths was considered to be low. In the omnidirectional receiver case, a slightly improved performance was recorded when the multipath was low, in comparison with the case of 50 incoming waves. These results completely agreed with those expected for the BER performance of the link.

4. Conclusions

In this paper, a simulation tool for estimating the performance of a communication link in terms of BER was presented. The fading conditions of the radio channel were generated according to the statistical model assumed. The case of the well-known Rayleigh channel model was examined, and the results were in excellent agreement with the corresponding analytic expression, as well as with recent work in the field. The simulation time was larger using the proposed method, but there exists the potential of simulating any arbitrary channel model. The case of the GBSBEM channel model was also depicted. A similar BER performance between the Rayleigh channel model and the GBSBEM model was shown when the number of multipath components was large. In the case of a directional receiver, there was a slightly improved performance of the link. Finally, the case of a small number of incoming waves was considered. An explicit improvement in the case of either an omnidirectional or a directional receiver when the number of multipath channels was small was shown. Along with the consistent behavior of the simulator for the Rayleigh fading channel case, a strong argument was made for its validity. The possibility of simulating arbitrary radio channel models from the perspective of the system performance in terms of BER was indicated. Further research in the field currently includes simulation of different statistical radio channel models and the case of frequency-selective fading, modeled with tapped delay lines, as described in [6, 9].

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Introducing the Authors

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Editor's Comments *Continued from page 121*

that have received good reviews. I have had a little experience with *Ad-Aware*, and found it satisfactory. Both require that you download and install the software, and then run a scan of your computer to locate known spyware that may be present. Both also need to be updated regularly. The software and the updates are typically free for non-commercial use, but require a paid license if used in a commercial environment. You need to read the descriptions associated with any spyware "suspects" these programs find on your computer *before* you allow them to remove the potential offenders: some software they will identify as spyware is software you want to be communicating over the Internet. Also, it appears that neither program will catch all spyware: most reviews I have read recommend using both.

The second and potentially better defense is to enable your firewall to screen and either prevent software on your machine for which you have not given prior permission from accessing the Internet, or ask your permission before allowing such software to access the Internet. Note that this is the "other side" of protecting a computer connected to the Internet. You want to protect your computer from malware and other threats *sent to* it from the Internet. You also want to protect your computer from *sending out* information you do not want sent out to the Internet. In *Norton*, this is done by implementing what *Norton* calls "Program component monitoring." With *Norton Internet Security* open, choose Options...Internet Security... and click on the Firewall tab. Check the box next to "Program component monitoring." Click OK to exit. You will then receive an alert essentially every time a program on your computer accesses the Internet, at least for the first access during an Internet session. Yes, it's a bit more bother. However, I would much rather know what is going out of my computer than to eliminate that bit of bother.

I mentioned that programs that try to automatically update themselves over the Internet can be a problem. That's because installing program updates can lead to all sorts of unexpected (and often, undesirable) software interactions or system instabilities on your computer. I don't like to install a program update unless I know that I need it, and – if I do need it – unless it has been released long enough that I can have some confidence that if there is (or, hopefully, was!) a significant bug in the update, someone else will have found it, reported it, and it has been fixed. I would much prefer to check the software publisher's Web site, find out what the update is supposed to do, decide I really need it, and download and install it in a controlled fashion than to have it automatically installed, possibly without my knowledge. By doing it myself, I at least have some chance of identifying what caused an unexpected effect on my system, should one occur. I may also have some chance of restoring my system to its pre-update state.

Of course, the above attitude with respect to updates is directly at odds with what appears to be a fundamental concept of *Windows XP*. Between security updates and patches (bug fixes), *Windows XP* seems to be averaging considerably more than an update per month. Indeed, that number appears to be exceeded by just the "critical" updates (mostly concerned with security). I wish I had a good answer for this. Short of sticking with older operating systems (which isn't a bad idea, if you can do it), I don't (and please don't send me messages saying "use *UNIX*," "use *LINUX*," or "use a Mac:" given the applications I need to run, these really aren't practical options). One thing I can and do recommend is applying *XP* updates one at a time, and checking for system stability and untoward interactions after each update. That at least makes it theoretically possible to identify what might be causing problems, and how to fix them.

"Pop-up" (or "pop-under") windows can be very annoying when you are browsing the Internet. They do just what their names imply: open new browser windows over (or under) the window you have open when you visit a Web site. They usually contain advertising. There are several ways to get rid of them. Newer versions of some browsers allow you to block them. In *Netscape 7.1*, use Edit...Preferences...Privacy & Security...Pop-up Windows to reach a box to check to block them. The next major service release of *Windows XP* is supposed to include this feature for *Internet Explorer*. You can also use a third-party program to block pop-up windows: searching the Web on names such as "Pop-up Blocker," "Pop-up Stopper," or "Pop-up Manager" will locate such software. I have no experience with these programs. *Norton* will also block pop-ups: Open *Norton*, in the center under Settings For double click on Ad Blocking, and check the box to block pop-up windows. However, be aware that blocking pop-up windows may interfere with the proper operation of some Web sites. In particular, banking and sites from which you purchase items with credit cards often use pop-ups.

Finally, if you have an "always on" high-speed Internet connection, I strongly suggest you install a hub immediately before the connection to your computer's Ethernet port or network-interface card (NIC). By turning this hub off (using either a built-in power switch, or a switch on a terminal strip into which the hub is connected for power) when you do not need to be connected to the Internet, you gain two features. First of all, you reduce (often, dramatically) the percentage of time your machine is connected to the Internet, and thus the proportionate number of threats to which your machine is exposed. Second, most hubs have lights that give at least a rough indication of activity. If your computer is directly connected to the Internet (rather than via a local-area network),

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