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Simulating Interference Issues: Bluetooth PANs and 802.11 b and 802.11g WLANs

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Title

Simulating Interference Issues between Bluetooth PANs and 802.11 b and
802.11g WLANs

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Abstract

Bluetooth Personal Area Networks (PANs) use the same 2.4 GHz ISM spectrum as IEEE 802.11b and IEEE 802.11g Wireless Local Area Networks (WLANs). The spread spectrum modulation used by the WLANs and the frequency hopping sequence used by the PANs requires them to periodically share the same frequencies. Operation of these PANs and WLANs simultaneously in the same location is expected to become increasingly common. When WLANs and PANs are collocated, the performance of each network can be degraded by interference from the other. Simulations were conducted to determine the impact of interactions between networks using these different standards. In the simulations, network performance degradation was determined as a function of the relative power and frequency offset of interfering signals. Simulation results of a Bluetooth network's Bit Error Rate (BER) with interference from 802.11b and 802.11g sources are presented. The performance degradation due to the 802.11b and 802.11g interference is compared to that produced by broadband noise interference sources. Simulations of an 802.11g network's BER with interference applied by a Bluetooth source is also described. The 802.11g performance is shown to be dependent on the proximity of the Bluetooth signal to the OFDM pilot sub-carrier frequencies. Error Vector Magnitude (EVM) measurements show the influence of the interfering Bluetooth signal on each of the OFDM sub-carriers. Finally, simulation of an 802.11b waveform's EVM with a Bluetooth interfering signal is presented. The BER produced in the 802.11b network can be estimated from the EVM measurements. These simulations improve estimates of interference between networks by accurately modeling desired and interfering signal modulation. In addition realistic models for transmitter and receiver intermodulation, phase noise, and filtering are used. All BER simulation results presented here use 100% collision rates between the desired and interfering signals. With this information, network throughput can be calculated for any network activity level.

Introduction

It had been another long and productive session of circuit simulation. Joe Engineer needed a break. "To reward myself, I'll download the complete works of Britney Spears mpeg collection", thought Joe. In his head he calculated that transferring the several hundred-megabyte video file would tie up the office 802.11b wireless network for several minutes. While he waited, Joe began sending emails with large attached files from his personal digital assistant over its Bluetooth link to his 3G cell phone. What happens next? Does interference between the Bluetooth and 802.11b networks frustrate the data transfers, or does Joe have a positive wireless networking experience? Coexistence of IEEE 802.11b and IEEE 802.11g wireless local area networks with Bluetooth personal area networks will be an important user satisfaction issue. These networks use the same 2.4 GHz spectrum and will often operate in the same locations. Evaluation of how the networks interact with one another is necessary to determine how they can be used simultaneously, while maintaining acceptable performance on each.

The IEEE 802.11b and proposed 802.11g standards (referred to together here as 802.11b/g) for Wireless Local Area Networks (WLAN) will serve to replace wired LAN computer networks. The 802.11b standard provides for payload data rates of 1, 2, 5.5 and 11 Mbps. DBPSK and DQPSK direct sequence spread spectrum modulation is used for 1 and 2 Mbps data transmission respectively. At 5.5 Mbps and 11 Mbps, CCK (Complementary Code Keying) modulation is specified for data transmission. 802.11g extends 802.11b with payload data rates up to 54 Mbps using OFDM modulation. In these WLANs, an access point radio wirelessly connects terminal devices like personal computers to each other and to the wired network. The maximum distance of terminal devices from the access point is 30 to 100 meters depending on the data rate. The transmit spectrum mask of the IEEE 802.11b/g standards require a channel's occupied bandwidth to be less than 22 MHz. Three non-overlapping 25 MHz spaced channels can coexist in the 80 MHz wide ISM band. Though channel agility is an option for 802.11b and g access points, many implementations are expected to be fixed on a single channel.¹

Bluetooth personal area networks are intended to provide wireless data links between cell phones, wireless headsets, personal digital assistants, personal computers and other devices in PANs. These devices

communicate with one another within a range of approximately 10 meters. Bluetooth signals are FSK modulated with a bit rate of 1 Mbps. The 2.4 GHz ISM band is divided into 79 Bluetooth channels that are spaced 1 MHz apart. Bluetooth networks frequency hop through a pseudo-random selection of these channels at 1600 hops per second.ⁱⁱ

Typically 802.11b/g WLAN access points will be stationary, and operating frequencies can be planned to minimize interference between WLANs. This is not the case for interaction between Bluetooth and 802.11b/g networks. Devices like cell phones need to maintain Bluetooth links to other devices in areas where 802.11b/g networks are operating. When Bluetooth networks hop onto a channel used by an 802.11b/g network, disruption of either or both networks is possible. Adaptive hopping procedures are being considered for a new Bluetooth standard to help it avoid frequencies being used by 802.11b/g networks. To create standards and designs that most effectively allow the two networks to coexist, it is necessary to know under what conditions interference between networks produces unacceptable degradations in performance. The connected solutions of Agilent Advanced Design System (ADS) and the virtual Vector Signal Analyzer (VSA) provide capabilities for analysis of Bluetooth and 802.11b/g networks.ⁱⁱⁱ

Several combinations of networks and interfering signals were simulated and analyzed using ADS and the software-based VSA. Results for the following combinations of desired signals and interfering signals are presented here.

- Bluetooth Performance with 802.11b Interference
- Bluetooth Performance with 802.11g Interference
- 802.11g Performance with Bluetooth Interference
- 802.11b Performance with Bluetooth Interference

A large number of parameters are included in these simulations. Accurate models of modulation for the desired and interfering channels are used. In addition, simulations include realistic models for transmit filters, receiver filters, amplifier non-linearity and phase noise. In all of the simulations presented here, results show BER when collisions occur between the desired and interfering networks. The interfering signal is applied at 100 percent duty cycle at a constant frequency. This is a worst case scenario in which every packet transferred on the network collides with interfering signal packets. In actual applications, the probability that a collision will occur will be less than 100 percent. The interfering signal power required to produce a specified BER when network collisions occur is needed to predict network performance. The probability of collisions can be calculated based on the expected transmit duty cycles of each of the networks. Using realistic collision probabilities and the BER produced with interference applied at 100% duty cycle, the actual performance of simultaneously operating networks can be predicted.

On average over an eight hour day, an 802.11b/g network may be expected to transmit only a small percentage of the time.^{iv} Therefore, the average BER a network experiences during a day will be low, even though the BER during collisions is high. However, average BER over a day may be a poor indicator of user satisfaction. The user may find network performance to be unacceptable if it is severely degraded during periodic intervals of simultaneous heavy network activity. Users, like Joe Engineer above, will find it inconvenient to use a network that is disrupted for intervals of several minutes by heavy traffic on an interfering network.

Simulations of Bluetooth Performance with IEEE 802.11b and IEEE 802.11g Interference

The bandwidth of a Bluetooth channel is less than 1 MHz, while 802.11b/g signals may be as wide as 22 MHz. To simplify calculation of a Bluetooth network's performance with 802.11b/g interference, a broadband noise source is sometimes used to represent the 802.11b/g interference. However, it is possible for simulations to include the details of the 802.11b/g modulation and full models of transmitter and receiver filters amplifiers and mixers. These simulations show the extent to which broadband noise assumptions are valid and allow circuit designers to identify modulation and filtering dependent effects.

The performance of a Bluetooth network was simulated with interference from an 802.11b source, an 802.11g source and broadband noise sources. The simulations determine the BER of the Bluetooth network as power and frequency offset of interfering signal are varied. The transmit filter and modulation characteristics which determine the interfering signal power density as a function of frequency offset are included in these simulations.

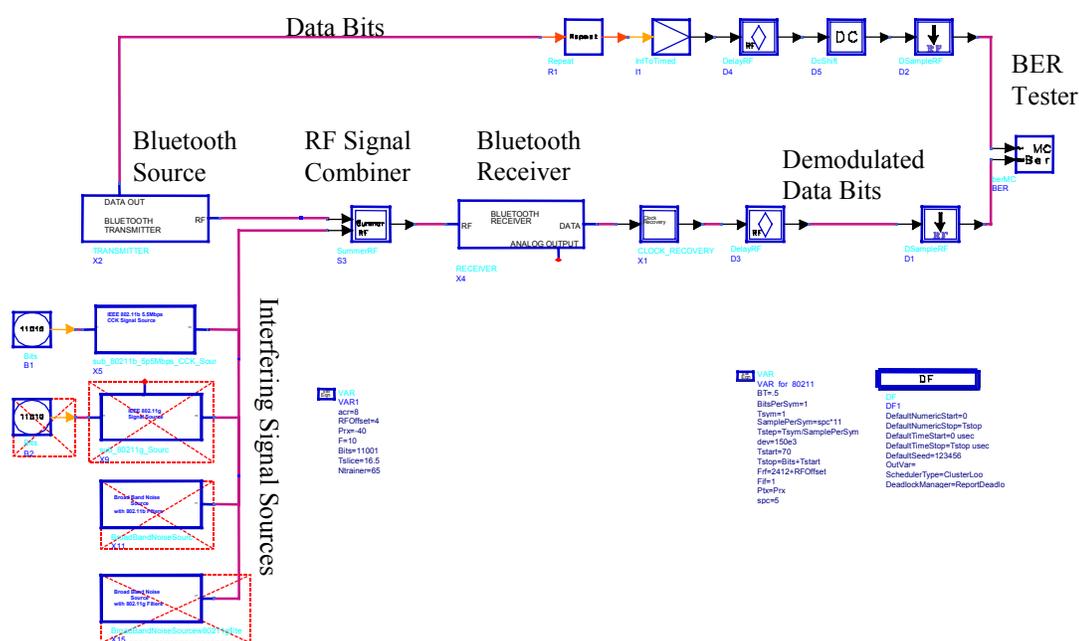


Figure 1 Schematic of Simulation of Bluetooth BER Performance with 802.11b/g Interference

The test bench shown in Figure 1 simulates the BER of a Bluetooth network in the presence of an interfering signal. The Bluetooth signal source has two outputs. One output provides a pseudo-random bit stream. The other provides a Bluetooth RF signal modulated by the same pseudo-random bit pattern. Four interfering signal sources, an 802.11b source, an 802.11g source, and two Gaussian broadband noise sources, are available. Only one of the interfering sources is enabled for each simulation; the other three sources are disabled. In Figure 1 the 802.11b interfering source is enabled. The red Xs on the other interfering sources indicate that they are currently disabled. The interfering RF signal and the Bluetooth RF signal are added together, and the combined signal is input to the Bluetooth receiver. The Bluetooth receiver uses models of amplifiers, mixers, filters, an FM demodulator, and a bit slicer with performance typical of an actual Bluetooth receiver. The Bluetooth receiver demodulates the RF signal, and outputs the resulting bit stream. The bit stream from the Bluetooth receiver is compared to the pseudo-random bit stream output by the Bluetooth signal source to determine the Bit Error Rate (BER) of the Bluetooth network.

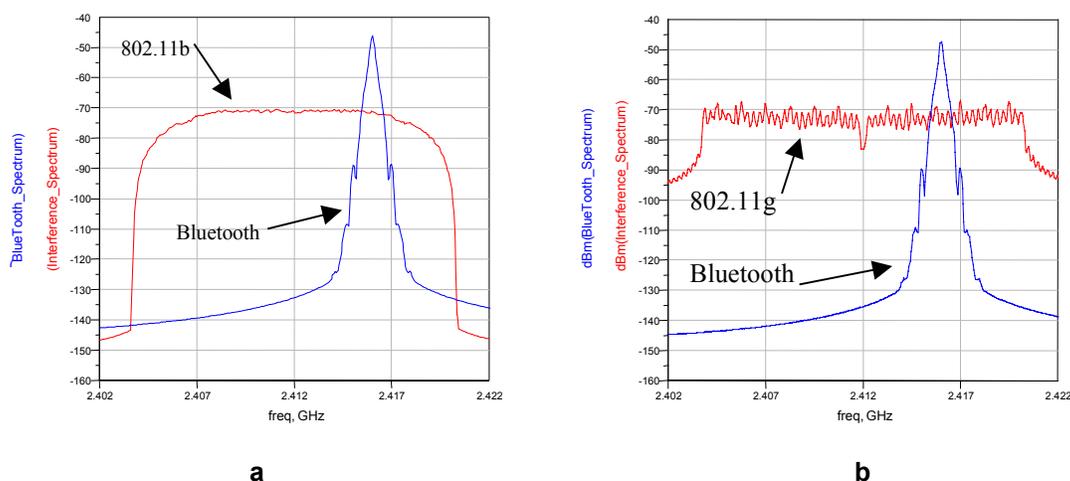


Figure 2 a) Spectra of Bluetooth signal and -8 dB 802.11b interference with 4 MHz offset
b) Spectra of Bluetooth signal and -8 dB 802.11g interference with 4 MHz offset

The 802.11b signal source in this analysis operates using 5.5 Mbps CCK modulation with a long preamble and header. A root-raised cosine filter with an 11 MHz bandwidth and an excess bandwidth of 0.5 is applied to the output signal. With this filter, 99% of the 802.11b spectrum occupies a 14.1 MHz band. Figure 2a) shows the simulation spectra of the Bluetooth RF signal and the interfering 802.11b signal. The total 802.11b signal power is 8 dB lower than the Bluetooth power in this plot, and the center frequencies of the two signals are offset by 4 MHz. Because simulations use realistic models for modulation sources, filters, and other receiver components, BER can be determined as function of frequency offset and interfering 802.11b power.

In this analysis, the 802.11g signal source uses components that are nearly the same as those used for the IEEE 802.11a 5 GHz WLAN standard. The only change that is made from the 802.11a standard is the RF frequency is shifted to the 2.4 GHz band. Broader transmit filters were used in the 802.11g transmitter than in the 802.11b source. The root-raised cosine transmitter output filters are 20 MHz wide with an excess bandwidth of 0.5. The red trace in Figure 2b shows the interfering 802.11g spectrum. The blue trace shows the Bluetooth spectrum. The 99 percent occupied bandwidth of the 802.11g signal is 16.25 MHz. In this plot center frequencies of the Bluetooth and 802.11g signals are offset by 4 MHz, and the total 802.11g power is 6 dB lower than the Bluetooth power.

The Bluetooth receiver has a 5th order Chebyshev baseband filter with a 1.14 MHz noise bandwidth. The ratio of the 802.11b occupied bandwidth to the receive filter noise bandwidth is 11 dB. The ratio of 802.11g occupied bandwidth to the receive filter noise bandwidth is 11.5 dB. Receiver components before the baseband filters have the entire 802.11b spectrum applied to them. In simulations presented here, power levels are low enough for these front end receiver components to operate linearly.

Two broadband noise sources are included in the Figure 1 simulation schematic to provide comparisons with the 802.11b/g interference. The noise sources have a normal Gaussian power density function. The output of one broadband noise source uses the same filters as the 802.11b source. The other noise output uses the same filters as the 802.11g source. The noise source power levels are measured in a 17 MHz band. The average noise power spectral density applied to the Bluetooth receiver is the same as the spectral density from the 802.11b/g sources.

To analyze the performance of the Bluetooth network, the threshold between acceptable and unacceptable performance is chosen to be a Bluetooth raw BER of 0.001. With Bluetooth packet lengths of 366 bits, this BER produces a raw packet error rate (PER) of 31 percent. Network performance with 31 percent raw PER is worse than insignificantly degraded and better than complete network failure. Bluetooth hops frequency through 79 channels over an 80 MHz frequency span. With the transmit filters used in this analysis, the 802.11b signal occupies 15 of the 79 channels. Collisions between an actual Bluetooth network and an

802.11b network will occur at most 19 % of the time. With a BER of 0.001 during collisions, the total PER will be about 5.9 %, assuming the error rate is much smaller when no collisions occur. This may not be acceptable for Bluetooth voice applications, but may be considered acceptable for data transmission.^v

Relative Interference Level Required to Produce 0.001 BER in a Bluetooth Receiver

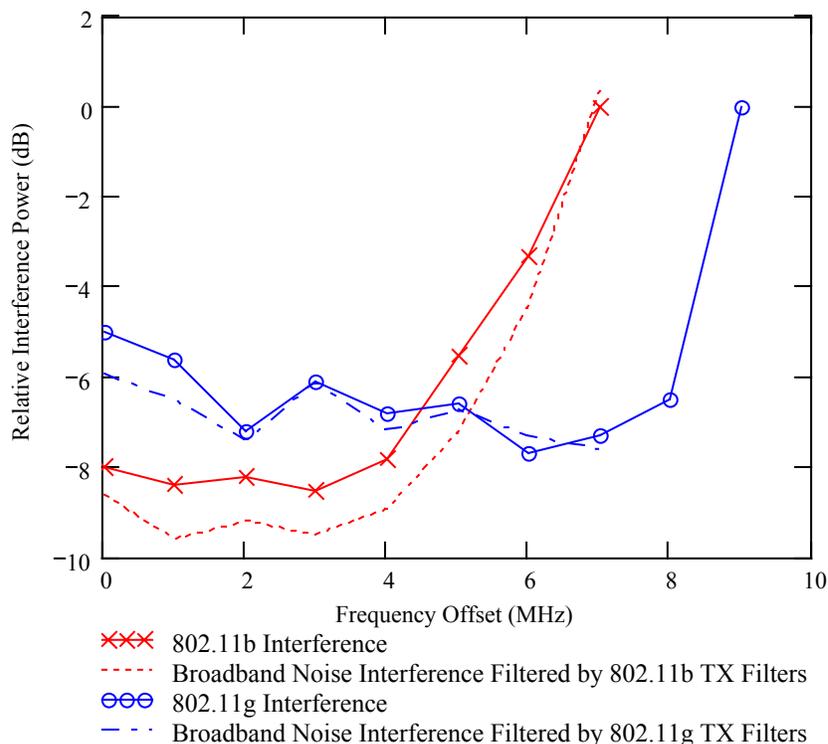


Figure 3 802.11b, 802.11g, and Broadband Noise Minimum Interference Power required to produce 0.001 BER in a Bluetooth Signal

Simulation results of a Bluetooth network with 802.11b, 802.11g, and filtered broadband noise interference are shown in Figure 3. The plot shows the minimum interference power that degrades BER in a Bluetooth receiver to 0.001. When the center frequencies of the Bluetooth and 802.11b signals are the same, an interfering 802.11b signal power 8 dB lower than the Bluetooth signal power degrades the Bluetooth BER to 0.001. The 802.11b interference power required to degrade the Bluetooth BER to 0.001 remains fairly constant as the signal offset increases to 4 MHz. As the frequency offset increases from 4 MHz to 7 MHz, the 802.11b interference power required to cause 0.001 BER increases at about 2.6 dB per MHz. The 802.11b transmitter filter is the primary factor determining the change in interference power for constant BER as frequency offset increases.

The plot, Figure 3, also shows results of simulations in which a broadband noise source interferes with the Bluetooth network. The broadband noise source has the same transmit filters as the 802.11b source. The broadband noise source power required to degrade Bluetooth BER to 0.001 is plotted. The broadband noise power level is about 1 dB less than the 802.11b power that produces the same BER.

The results of simulations of 802.11g interference with a Bluetooth network also are plotted in Figure 3. Up to 4 MHz offset, the 802.11g signal power that degrades Bluetooth BER to 0.001 is greater than that for 802.11b interference. This is because the 802.11g signal is spread over a wider bandwidth than the 802.11b signal, so the spectral power density of the 802.11g signal is lower when the total signal power is the same.

At 0 MHz offset, the 802.11g power is particularly high due to the fact that center OFDM sub-carrier is not used.

The interference produced in a Bluetooth network by broadband noise source using the same transmit filters as the 802.11g source is also simulated, and results are shown in Figure 3. The transmit filter passband of the 802.11g source is 20 MHz wide. This is significantly wider than the 802.11g occupied bandwidth, so the filters have little effect on the spectral shape of the 802.11g signal within the occupied bandwidth. The total noise source power is measured over a 17 MHz bandwidth to make the average noise power density in the 17 MHz span the same as that of a 802.11g source with equivalent total power. The broadband noise source power producing 0.001 BER in the Bluetooth network is very close to the power of an interfering 802.11g source producing the same degradation.

The carrier to interference ratio in the Bluetooth receiver is calculated by dividing the interference power in the Bluetooth receiver noise bandwidth by the received Bluetooth signal power. In these simulations the average carrier to interference ratio in the Bluetooth receive band required to produce 0.001 BER is 18.6 ± 0.3 dB for all the interference sources. Using broadband noise sources as interference instead of 802.11b/g modulated sources provides a reasonable estimate of Bluetooth performance. When making this approximation, the power of the noise source in the Bluetooth receiver bandwidth must be the same as would be produced by an 802.11b/g source. In many cases, designers may choose to include the full details of 802.11b/g modulations and filters in simulations, so interference spectral densities are accurately modeled.

Simulation of 802.11g Performance with Bluetooth Interference

802.11a and 802.11g use OFDM modulation that divides 16.25 MHz of bandwidth into 52 sub-carriers 312.5 kHz wide. An OFDM data packet consists of a preamble, a header and data block. In the data block, 48 sub-carriers are used to transmit data. These carriers may be modulated with BPSK, QPSK, 16-QAM, or 64-QAM depending on the data rate. Four sub-carriers are used as pilot signals in the data block. The 802.11g receiver uses the pilot signal as reference for phase and amplitude to demodulate the data in the other sub-carriers. The pilot signals allow the receiver to compensate for phase and amplitude distortion of the OFDM signal. Numbering the OFDM sub-carriers of a channel from -26 to +26, pilot signals are on channels -21, -7, +7, and +21. When the 1 MHz wide Bluetooth interference is applied to the 802.11g signal, only a few of the sub-carriers are directly affected. Bluetooth interference that falls on the pilot sub-carrier can produce errors in the phase and amplitude correction the receiver uses when demodulating the data sub-carriers.

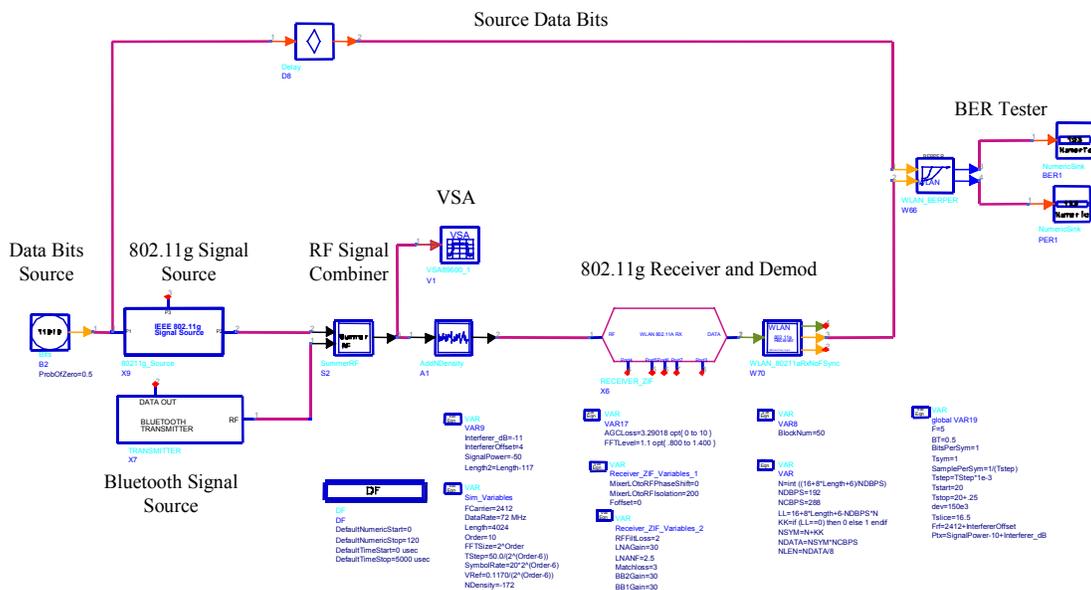


Figure 4 Schematic of Simulation of 802.11g BER Performance with Bluetooth Interference

Figure 4 shows the test schematic used to simulate 802.11g BER with interference from a Bluetooth source. The 802.11g RF waveform is generated from a pseudo-random bit stream. An interfering Bluetooth RF signal is added to the 802.11g RF waveform, and the combined RF signal is input to a 802.11g receiver. The 802.11g receiver demodulates the signal and outputs a bit stream which is compared to the bit stream used to create the 802.11g RF signal. In simulations presented here, the data rate of the 802.11g signal is 48 Mbps. At 48 Mbps, the OFDM data sub-carriers use 64 QAM modulation.

**Bluetooth Power Relative to 802.11g Power
to Produce 0.001 BER from the 802.11g Receiver
as a Function of Center Frequency Offset**

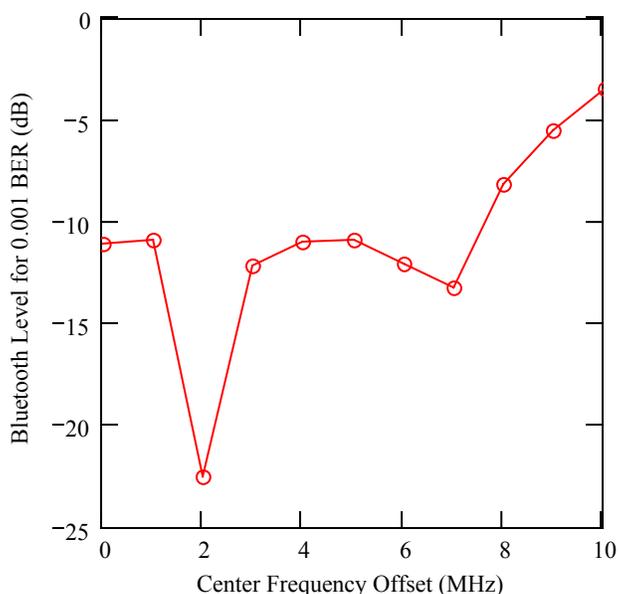


Figure 5 Bluetooth Interference Power Relative to 802.11g Power Required to Produce 0.001 BER

Figure 5 shows simulation results for an 802.11g network with interference from a Bluetooth transmitter. The relative Bluetooth signal level that produces a BER of 0.001 in the 802.11g link is shown versus the frequency offset of the Bluetooth and 802.11g signal center frequencies. At 0 MHz offset, -11 dB Bluetooth signal produces 0.001 BER. Between 0 and 5 MHz offset, the Bluetooth signal power required to produce 0.001 BER is nearly constant, except at 2 MHz offset. When the Bluetooth and 802.11g signals are offset by 2 MHz, Bluetooth interference 22.5 dB below the 802.11g signal level produces 0.001 BER in the received 802.11g signal. The 802.11g network is 11 dB more sensitive to degradation at 2 MHz frequency offset than it is at 1 MHz or 3 MHz offset. At 7 MHz offset, the Bluetooth power drops to 13 dB, and then it increases about 3 dB/MHz from 7 to 10 MHz offset.

The increase in 802.11g network degradation at 2 MHz offset is due to the Bluetooth signal interfering with an 802.11g pilot sub-carrier 2.19 MHz from the 802.11g center frequency. An increase in degradation also occurs at 6 MHz and 7 MHz offset, but is not as strong. The pilot sub-carrier at 6.56 MHz offset is between the 6 and 7 MHz offset channels, so only the edges of the 1 MHz wide Bluetooth signals fall on the pilot sub-carrier.

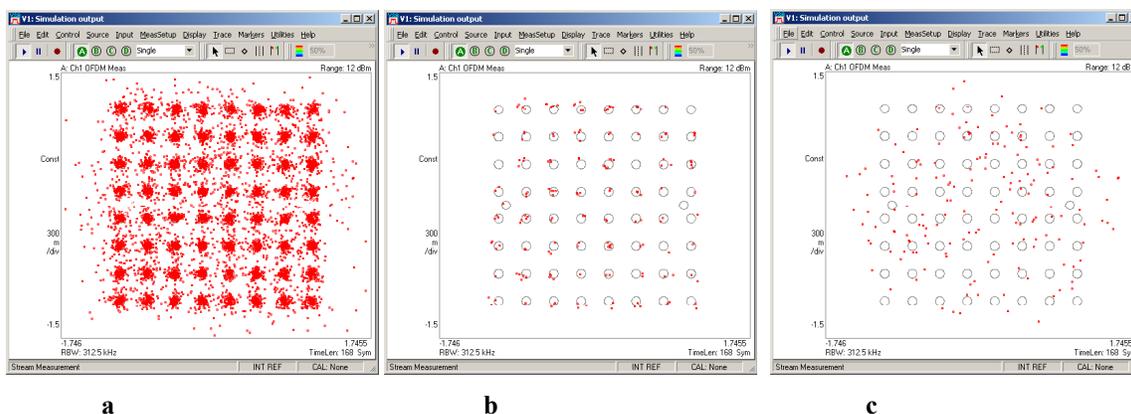


Figure 6 802.11g OFDM Constellation with -11 dB Bluetooth Interference 4 MHz Offset
a) All Sub-Carriers
b) Sub-Carrier Number 1
c) Sub-Carrier Number 13

Because the Bluetooth channel is only 1 MHz wide, it does not affect all of the OFDM sub-carriers equally. For example, when the Bluetooth interfering signal is offset 4 MHz from the 802.11g center frequency, most of the Bluetooth power will be applied to the 12th and 13th OFDM sub-carriers. A software-based Vector Signal Analyzer (VSA) can be used to investigate the effects of narrow-band interference from Bluetooth on 802.11g OFDM sub-carriers. Figure 6 shows the simulated 64 QAM constellation of a 48 Mbps 802.11g signal with a -11 dB Bluetooth interfering signal captured with a VSA. The Bluetooth signal is offset 4 MHz from the 802.11g signal center frequency. Figure 6a) shows the constellations of all the OFDM sub-carriers simultaneously. Though most data points are within 5% Error Vector Magnitude (EVM) circles of the ideal constellation points, there are many data points with larger EVM. The VSA allows those data points to be investigated further by displaying the 64 QAM constellations of each OFDM sub-carrier individually. Figure 6b) shows the constellation of OFDM sub-carrier number 1, which is 312.5 KHz from the 802.11g center frequency. This sub-carrier is 4.7875 MHz from the interfering Bluetooth signal. Most data points have an EVM of less than 5%. The Bluetooth interference effect on the number 13 OFDM sub-carrier is much greater, as is seen in Figure 6c. Few of the data points have less than 5% EVM. The large disruption of this sub-carrier is expected because it is 4.0625 MHz from the 802.11g center frequency and is very near the Bluetooth center frequency.

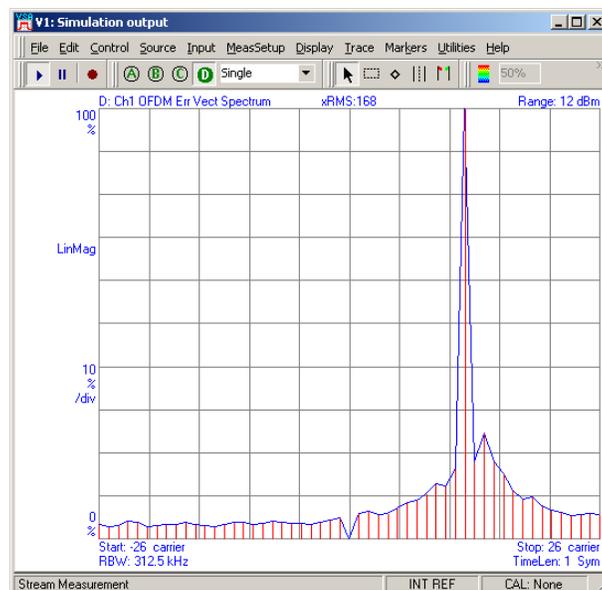
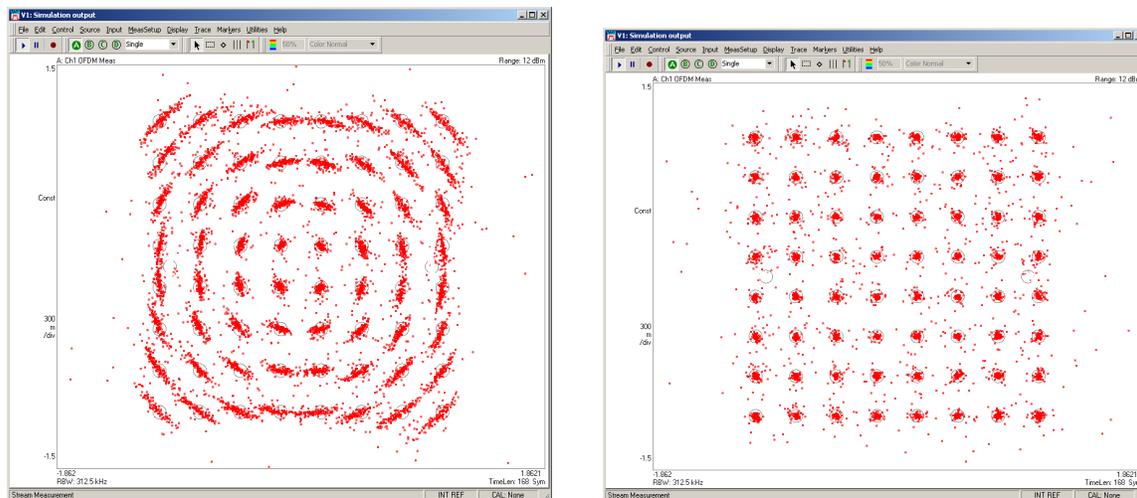


Figure 7 EVM of 802.11g OFDM Sub-Carriers with -11 dB Bluetooth Interference 4 MHz Offset

The simulated EVM of each OFDM sub-carrier was analyzed using the software-based VSA. The results are shown in Figure 7. For sub-carriers number -26 through 0, the EVM is between 2 and 5 percent rms. The sub-carriers nearer to the Bluetooth interfering signal have larger EVM. Sub-carrier number 12 has an EVM greater than 100%. The power of the Bluetooth signal is 11 dB less than the total 802.11g power, but its power is 6 dB greater than the power of the individual OFDM sub-carriers. Therefore, the EVMs of sub-carriers with frequencies very close to that of the Bluetooth signal are expected to be very large.



a

b

Figure 8 All 802.11g OFDM Sub-Carriers Constellation with -21 dB Bluetooth Interference
a) 2 MHz Frequency Offset
b) 4 MHz Frequency Offset

Pilot sub-carriers in a OFDM signal are used as phase and amplitude references for demodulating data sub-carriers. Bluetooth interference on a pilot sub-carrier can cause errors in the demodulation of data sub-carriers. Figure 8a) and b) show the 802.11g constellations with the interfering Bluetooth signal offset 2 MHz and 4 MHz respectively. The power of the interfering Bluetooth signal is 21 dB below the 802.11g signal for both cases. The interference at 2 MHz offset causes errors in the reference phase used for demodulation of all sub-carriers. This phase error show up as circular smearing of the 64 QAM constellation of Figure 8a). In Figure 8b) the interference does not fall directly on a pilot and the constellation errors are more randomly scattered.

Error Vector Magnitude of OFDM Sub-Carriers

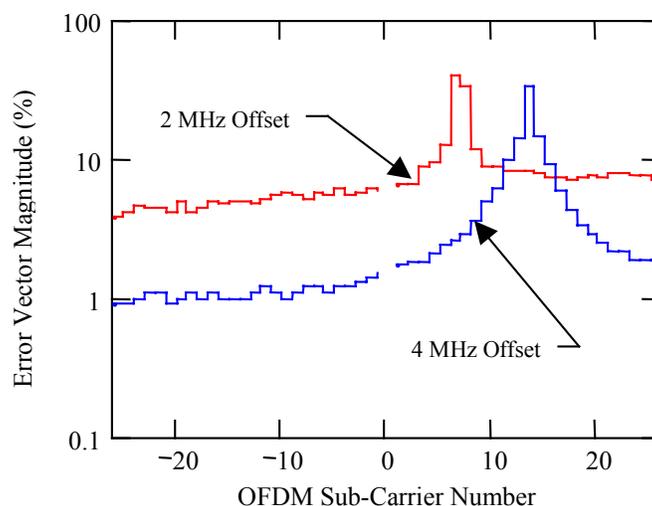


Figure 9 EVM of 802.11g OFDM Sub-Carriers with -21 dB Bluetooth Interference
Red Trace Frequency Offset 2 MHz
Blue Trace Frequency Offset 4 MHz

The EVM of each sub-carrier of the OFDM modulation is shown in Figure 9. The red trace and blue trace show the EVM when the interfering signal offset is 2 MHz and 4 MHz respectively. The interfering signal power is -21 dB for both cases. The maximum EVM occurs in the sub-carriers closest in frequency to the interfering signal and has about the same magnitude for both cases. Moving away from the interfering signal, the EVM drops much lower when the interference does not corrupt a pilot signal. Pilot signal phase errors cause errors in demodulation of all of the sub-carriers.

802.11b Performance with Bluetooth Interference

The final case to be investigated is the corruption of an 802.11b network by an interfering Bluetooth signal. In these simulations, a software-based VSA is used to determine the EVM produced in a 5.5 Mbps CCK 802.11b signal when an interfering Bluetooth signal is applied. Figure 10 shows the constellation produced in one of these simulations. The Bluetooth interference power is 20 dB below the 802.11b power. The Bluetooth and 802.11b signals are offset by 3 MHz. The FSK modulated Bluetooth interference produces a constant EVM in the CCK constellation of about 10%. The measured constellation points with constant EVM produce circles around the ideal points of the constellation.

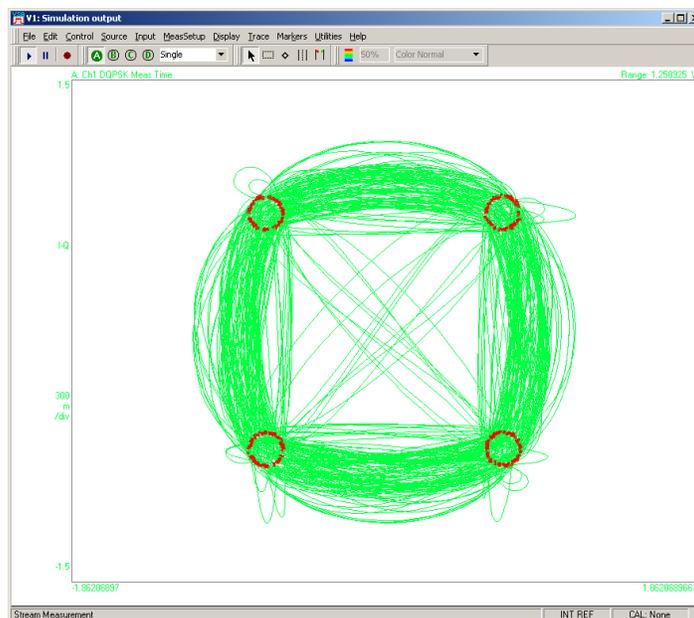


Figure 10 Constellation of CCK Modulated 802.11b Signal with -20 dB Bluetooth Interference

Figure 11 shows the error vector magnitude produced in a 5.5 Mbps CCK signal as a function of frequency offset. The Bluetooth interfering signal is 20 dB below the 802.11b signal. From 0 to 5 MHz frequency offset the EVM produced is about 9.5%. As frequency offset increases beyond 5 MHz, the receive filters reject the Bluetooth signal, and the EVM is reduced. Figure 12 shows the increase in EVM as the interfering Bluetooth signal power is raised from -20 dB to -10 dB. For this plot, the offset is constant at 4 MHz. EVM is seen to increase monotonically from 10 percent to 30 percent.

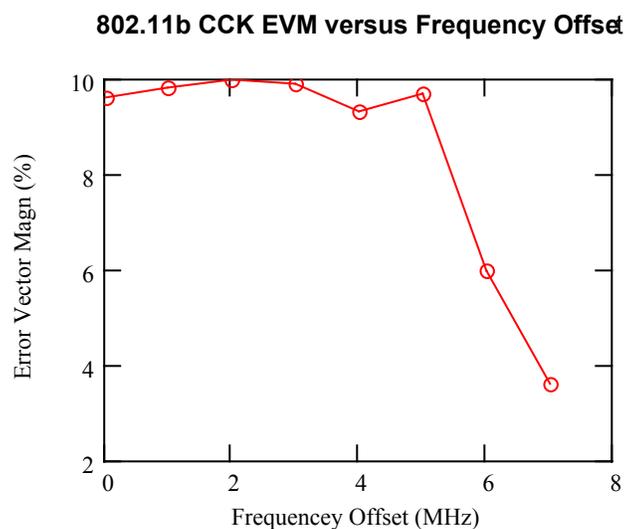


Figure 11 CCK Modulated 802.11b EVM with -20 dB Bluetooth Power versus Frequency Offset

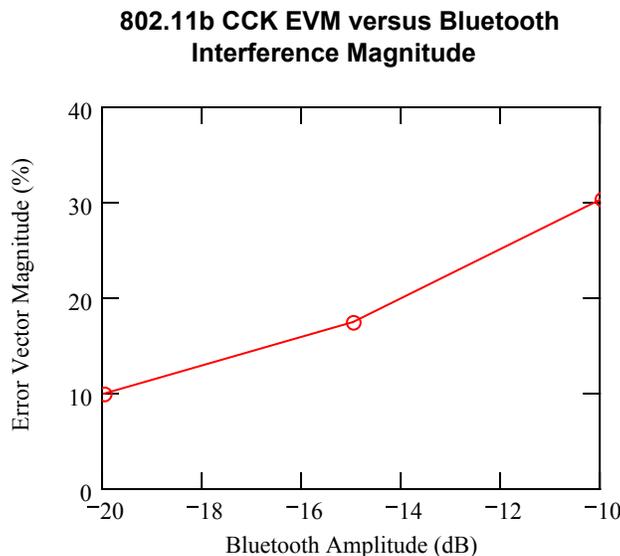


Figure 12 CCK Modulated 802.11b EVM with 3 MHz Offset Bluetooth Interference versus Bluetooth Interference Power

EVM data can be used to calculate BER for the CCK modulated signal. It should be noted that because the 802.11b EVM due to the Bluetooth interference is constant, the root mean square (rms) EVM is equal to the peak value. Fewer bit errors will be produced with a 10 percent rms EVM than would be the case if the peak EVM were much larger than the rms value. In order to produce bit errors, the EVM associated with a CCK chip must be large enough to place the demodulated constellation point in to the wrong quadrant in the I-Q plane. Errors will begin to occur when the circles of constellation points, like those in Figure 10, become large enough to overlap. When the EVM is 70.7 percent, the circles of constellation points will just touch one another. No errors will occur demodulating the CCK signal with a constant EVM less than 70.7 percent. As EVM increases above 70.7 percent, demodulation errors will increase quickly. In Figure 12, the EVM due to -10 dB Bluetooth interference is 30 %. Bit errors will not be produced in the CCK modulated 802.11b signal due to Bluetooth interference at this level. Processing gain of the CCK modulation provides additional protection from bit errors.

Conclusion

Interference from 802.11b/g signals on Bluetooth networks can be approximated by determining the Bluetooth degradation that will be produced by broadband noise interference. By including models of 802.11b/g transmit filters in simulations of broadband noise interference with Bluetooth networks, performance degradation as a function of frequency offset can be determined.

Degradation of an 802.11g network by an interfering Bluetooth signal is much more severe when the Bluetooth frequency is very near an OFDM pilot sub-carrier. The degradation of an 802.11g network by an interfering Bluetooth signal that falls directly on the pilot signal in the 7th OFDM sub-carrier is the same as that produced by 10 dB stronger Bluetooth signals falling on OFDM data sub-carriers. Simulation can include the effects of 802.11g and Bluetooth modulation and system filters to determine 802.11g network performance as a function of frequency offset.

Simulating the EVM produced in an 802.11b CCK modulated waveform provides an estimate of 802.11b network performance in the presence of an interfering Bluetooth signal. To produce enough bit errors to noticeably degrade the performance of a CCK modulated 802.11b network, an interfering Bluetooth signal's power must be higher than -10 dB compared to the 802.11b signal.

Simulations show that interference between 802.11b/g networks and Bluetooth networks can be significant when used simultaneously the way Joe Engineer does. His experience downloading files on his WLAN while there is large amount of activity on his PAN will be determined by the relative signal power of 802.11b/g and Bluetooth signals at each receiver. In some cases he may be frustrated by his simultaneous wireless networking experience. In other cases, he will be unaware of the interference. ADS simulation of networks^{vi} using all of these standards is a powerful tool for creating designs and standards that will ensure the highest possible level of user satisfaction.^{vii}

Acknowledgement

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About Innovative Wireless Technologies

Innovative Wireless Technologies (IWT) provides industry proven wireless and telecommunications design services. IWT's services range from consulting to turnkey product development. Focusing on wireless communications design, IWT prides itself on helping customers with or without wireless experience develop products quickly and cost effectively. More information can be found on the IWT web site at: <http://www.iwtwireless.com/>

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^{iv} Jaap C. Haarstsen, Stefan Zürbes, Bluetooth voice and data performance in 802.11 DS WLAN environment, Ericsson SIG publication. 1999-05-31 Rev C

^v Ibid

^{vi} To learn more about ADS and simulating wireless networks, visit <http://eesof.tm.agilent.com/index.html>

^{vii} To learn more about practical applications of wireless network simulation, visit <http://www.iwtwireless.com/>

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