Tools for Evaluating Bluetooth Coexistence
with Other 2.4GHz ISM Devices

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Introduction

Bluetooth™ (BT) technology is designed to operate in the 2.4 GHz unlicensed radio (UL) spectrum. Usage models for BT products indicate a strong likelihood BT will be collocated with a variety of different wireless devices operating within the same band. Understanding how these different wireless services coexist when they are collocated is a significant issue. It is important the “user experience” is positive when using wireless enabled products. As wireless applications move from ones of convenience to reliance, the capability to predict potential interoperability issues is imperative, in order to forestall negative consumer opinion.

The paper presents tools for evaluating coexisting between BT and WLAN based on research conducted at the Wireless & Signal Processing Laboratory, University of Wisconsin-Milwaukee in conjunction with Communication/RF Group, Innovation Center of Eaton Corporation [1-7]. The research has focussed on developing a methodology for evaluating coexistence issues based on a stochastic model of the interoperability process, i.e., coexistence model. The coexistence model provides a prediction of the network performance for different scenarios based on statistical inference. Network performance issues such as packet error rate and transmission latency can be evaluated.

As born out by our research and the work of others [8-13], BT coexistence is significantly impacted by the operational environment, i.e., hospital, factory floor, office space, or etc. The performance impact due to the variation in the BT operational location presents two viewpoints for coexistence evaluation: site-non specific and site specific. In general, BT product developers will be designing communication systems required to work in a variety of environments, i.e., site-non specific. The current coexistence model provides a set of analytical tools well suited for evaluating this issue. The model can assist in answering questions such as, “What type of environments will cause my BT application to degrade?” On the other hand, the end user is concerned whether or not the BT application will be impacted within their operational
environment, i.e., site specific evaluation. Current work is focused on extending the tool set to include site specific analysis.

In the next section an overview of the methodology used in developing the coexistence model is presented. This is followed by a brief overview of both BT and IEEE 802.11b. Based on the current state of the wireless networking market, the 802.11b is one of the dominate wireless local area networks (WLAN) and therefore a central concern for coexistence with BT wireless personal area networks (WPAN). The coexistence issues between BT and 802.11b are then discussed, i.e., RF environment and the interfering network parameters. An example is then presented to illustrate the approach. This is followed by extensions to the coexistence model and general conclusions.

**Multilevel Approach for Coexistence Model**

The coexistence model was developed on a multilevel approach in order to address issues associated with the degree of uncertainty in the BT operational environment. Prior work on the coexistence issue of WLAN and WPAN [8-13] focused primarily on a single or a few environments and often relied heavily on Monte Carlo simulations. Their work provides insight into the coexistence problem and part of the insight is the impact the environment has on the coexistence performance. Therefore, the coexistence model was developed to address these concerns. The approach is based on three components:

1. **General Analytical Model** - Stochastic model with a closed form solution provides a method to obtain understanding of coexistence within an arbitrary operational environment. This methodology helps to examine coexistence when there is uncertainty in the expected network traffic activity or uncertainty in the radio environment.

2. **Empirical Testing & Modeling** – Development of an understanding of essential parameters based on simple scenario tested under controlled environments. These results are also used in supporting analytical model development and results used to validate analytical model assumptions and behavior.

3. **Site Specific Model** – This is built upon both the extensive literature associated with RF propagation modeling within a specific location and the general analytical model to provide coexistence evaluation for a specific installation. If information is available concerning the deployment site, then site-specific analysis can be used. Using this approach, then within a specified degree of accuracy the signal powers can be estimated within the building layout.
Often information concerning the deployment site is not available and therefore general RF signal propagation models are required.

**Bluetooth and IEEE 802.11b Overview**

Both IEEE 802.11b and BT operate in the 2.4 GHz UL band. Wireless devices operating in this band are required, in general, to use a spread spectrum (SS) technique. BT is a Frequency Hopper (FH) and 802.11b uses Direct Sequence Spread Spectrum (DSSS). Both wireless services use a packet switched protocol and for data transmissions, they both utilize an acknowledgement to improve link reliability.

For BT, the bandwidth allocated to each frequency hop channel is 1 MHz with a hop rate of 1600 hops/second. The 2.4 GHz UL band occupies 83.5 MHz, so keeping in mind guard bands, only 79 unique frequency channels are allocated for each hopping code. Within the BT specification, there are several different packet structures. The basic packet timing is 625 µs per slot. Typical transmit power for BT is 1 mW or 0 dBm (Class 3 devices), although the standard describes other options.

IEEE 802.11b uses DSSS to effectively spread the signal in the frequency domain, this is achieved by encoding the data stream at the transmitter with a spreading code at a higher rate than the data stream. IEEE 802.11b signal’s transmission bandwidth is 22 MHz with a raw data rate of up to 11 Mbps. The multiple access is based on Carrier Sense Multiple Access with collision avoidance (CSMA/CD). It allows for efficient medium sharing without overlap restrictions. The maximum allowable packet size is 1500 bytes requiring 1210 µs to transmit (assuming 11 Mbps). For IEEE 802.11b based WLAN systems, minimum spacing of 30 MHz between carrier frequencies is specified to avoid interference. Therefore, within the same proximity up to three IEEE 802.11b systems could be deployed in 83 MHz of available band. Typical transmit power levels vary between 30 to 100 mW (15 to 20 dBm).

**Coexistence Overview**

Evaluating the impact of BT on IEEE 802.11b or viceversa involves assessing the likelihood the two signals occupying the same time and frequency space. Figure 1 illustrates the coexistence mechanisms between the IEEE 802.11b and BT wireless services.

Detailed analysis and modeling which considers probability of the two signals being time & frequency coincident has been addressed in [1, 2, 4].

A central issue in evaluating frequency coincidence is determining if the interfering signal has sufficient power relative to the desired signal at the intended receiver in order to cause
interference. Notice that this can occur even when the interfering signal is not within the main frequency band of the desired service. This issue is addressed by evaluating co-channel and adjacent channel interference effect of two wireless services. An Empirical test bed was used to evaluate & verify key parameters used for estimating interference immunity of both services with respect to each other [3, 6, 7].

**Wireless Propagation**

A central mechanism influencing the coexistence evaluation is the RF signal propagation. The quality of service for any wireless service is dependent upon received signal power and interfering signal power at the receiver. The variation in received signal strength is illustrated in Figure 2. In the figure, signal attenuation is shown within two building layouts. For both layouts the walls are at the same location, but different building materials are used. Two transmitters, AP, and corresponding receivers, STA, are depicted in each layout. In each case, the AP to STA distance is the same, but the received signal strengths can vary over two orders of magnitude (25 dB).

As can be seen by this example, variations in location can have a significant impact on the received signal quality from the desired transmitter. It is essential to take into account this variability when evaluating the coexistence, especially when the location of the BT deployment is unknown, non site specific evaluation. Drawing conclusions concerning a BT application performance based on generalizing coexistence results based on a single or a few scenarios is at best risky. In the formulation of the coexistence model, an industry standard stochastic model for
evaluating wireless signal propagation is used, exponential path loss model with log-normal shadowing. This model is designed to evaluate signal propagation under general RF environmental conditions.

Network Parameters

In order to evaluate the performance of the network in the presence of interference, it is required to define a “network performance criteria”. This has a direct relation with the network traffic model (amount of data, type of data, and others). Both BT and IEEE 802.11b networks can be used to form ad-hoc networks and therefore traffic models that characterize their deployment and traffic activity can have a significant degree of uncertainty and variability. IEEE 802.11b is often deployed as a wireline replacement and therefore traffic activity can be modeled using similar techniques used in evaluating wireline network activity. BT on the other hand represents a new networking strategy with a less defined typical deployment strategy.

In the coexistence model, the BT network parameters are defined as the Loading factor, the Activity level and the BT Piconet density. Loading factor represents the utilization of the link, e.g., SCO link with HV3 uses one out of six time slots. Activity level is a measure of how
often a BT piconet is active. BT piconet density represents the expected number BT piconets within a given area, piconets per meter squared.

The network parameters and RF environment parameters affects the probability where a collision between two wireless messages can occur, i.e., probability of collision. Probability of Collision, \( \Pr[C] \), is defined as “event when desired service packet is corrupted by interferer so as retransmission is required”\([1, 4]\).

Network performance can be evaluated from a number of viewpoints using various measures of performance (MoPs). The relevance of each MoP is dependent on the specific network requirements. Three networks MoPs have been developed: Expected Packet Error Rate, \( E[PER] \), Number of Packet Retransmissions (RT) and Expected Transmission Latency (S). These MoPs have been mapped into \( \Pr[C] \), thereby providing a closed form solution for evaluating network performance issues based on the underlying network and RF environment parameters.

**Example of the Analytical approach**

To illustrate the approach, coexistence is evaluated for the impact of BT piconets on IEEE 802.11b WLAN network taking into account six independent variables

2. Radio Propagation Parameters:- Extensive literature available on typical values for different types of environments, e.g., office building with soft partitions vs. warehouse. A range of parameter values is straight forward to evaluate.

By fixing the radio propagation parameters, a specific probability of collision can be evaluated over the BT network parameters, Figure 3 illustrates the resulting graph. The curve describes a surfaces within the BT parameters space for \( \Pr[C]=0.2 \) (20% probability). This could be viewed as a performance boundary, i.e., if a specific application falls on the right hand side of the curve, then the performance is satisfactory. The specific performance boundary will be application dependent, and will need to be defined by the BT product developer. In the figure two specific BT scenarios are indicated by \( \Delta_L \) and \( \Delta_H \). The parameters used for each of these scenarios are summarized in Table 1. For the light scenario, \( \Delta_L \), the probability of collision is approximately 0.07 (7%). This is an acceptable value since it is less than 20%. For the heavy scenario, \( \Delta_H \), the probability of collision is approximately 0.34 (34%). In this case the 802.11 network will have a degradation higher than the established by the developer.
Table 1  BT piconet traffic models for the light and heavy network activity scenarios $\Delta_L$ and $\Delta_H$ respectively.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Traffic</th>
<th>BT Packet Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta_L$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Telephony</td>
<td>10 calls/day @ 2 min/call</td>
<td>HV3</td>
</tr>
<tr>
<td>Email</td>
<td>15 emails/day @ 10 kbytes/email</td>
<td>DH1</td>
</tr>
<tr>
<td>$\Delta_H$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Telephony</td>
<td>10 calls/day @ 2 min/call</td>
<td>HV3</td>
</tr>
<tr>
<td>Email/Printer/Scanner/PC Wire Replacement</td>
<td>20 Mbytes/day</td>
<td>DH1</td>
</tr>
</tbody>
</table>

Site Specific Evaluation Tool

The coexistence model developed above can be extended as evaluation tool for any application being targeted by a BT developer. Coexistence Evaluation tools can be used to evaluate network performance for site-specific analysis or it can be used to define performance bounds for non-site specific scenarios.
It is straightforward to extend this analysis into the site-specific model and evaluate with the specific ranges of network and radio propagation parameters. Consider a normal office 20 meter x 30 meter as shown in Figure 4. The office has concrete walls and partitioned cubicles in between. The effective coverage area within this specific floor plan is evaluated for IEEE802.11b in the presence of BT. Both light WPAN user scenario $\Delta_L$ and heavy WPAN user scenario $\Delta_H$ were evaluated and shown in Figure 5 (a) & (b). As illustrated, for the $\Delta_L$ scenario, the WPAN

Figure 4  Coexistence Analysis for Site Specific Area (a) Heavy BT Scenario (b) Light BT.
is unlikely to cause interference, if a 20% probability of collision (expected packet error rate of 20%). On the other hand, for the $\Delta_H$ scenario, a significant portion of the 802.11 coverage region falls below the desired performance criteria.

The results presented are for a specific MoP. Results will be different depending on each applications requirements. The coexistence model can help in answering general questions, e.g., Will BT or 802.11 performance satisfy an applications requirements or will coexistence be an issue.

**Optimization tools**

Based on the research performed, optimization tools are being developed to help minimize the coexistence issues. The optimization tools can help in predicting performance bounds for wireless LAN in presence of BT interference. To predict the performance of the network, the number and location of the access points may be optimized. In addition, the impact on the network on expected ad-hoc BT piconets within the same location can be minimized. Also these optimization tools can help in developing a framework where tradeoffs like Bandwidth vs. number of nodes vs. Latency vs. Reliability vs Data Rates, etc. can be addressed.

**Conclusion**

The coexistence model was developed with focus on addressing different levels of uncertainty in the BT application’s environment, where the environment encompass both the RF environment and the wireless network environment. The model was developed based on extensive research by University of Wisconsin & Eaton Corporation-Innovation Center, which involved developing analytical framework, Empirical Modeling & Monte Carlo simulations. Efforts are underway to develop Tools for evaluating & optimizing coexistence based on the above research.

The coexistence model developed herewith provides a tool for distinguishing the conditions where wireless network deployments are likely and unlikely to suffer performance degradation in presence of each other. Based on this evaluation tool, optimization tools are being developed which can help in minimizing the impact of two wireless services without any change in the specifications. This should act as an important tool for BT developers who can optimize the performance of their products by predicting the performance in presence of interferers.

**References**


