IEEE 802.11 AND BLUETOOTH COEXISTENCE ANALYSIS METHODOLOGY [1]

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Abstract

As unlicensed (UL) band utilization for daily office functions increases, an understanding of how different wireless services, operating in the same band, may impact each other becomes an important issue. Both Bluetooth wireless personal area networks and IEEE 802.11 wireless local area networks share the same 2.4 GHz UL band and provide complimentary wireless solutions for connectivity. A method was developed for examining wireless services coexistence in order to evaluate the impact interference may have on network performance. The methodology for the analysis was centered on deriving a closed form solution for the probability of collision in terms of the network and radio propagation parameters. The approach is illustrated by examining the coexistence between 802.11b and Bluetooth within typical operational ranges for both network traffic and RF environments.

1 Introduction

As unlicensed (UL) band utilization for daily office functions increases, an understanding of how different wireless services, operating in the same band, may impact each other becomes an important issue. Both BT wireless personal area networks (WPANs) [1, 2] and IEEE 802.11 wireless local area networks (WLANs) [3] share the same 2.4 GHz (UL) frequency band and provide complimentary wireless solutions for connectivity. Coexistence analysis between the IEEE 802.11 and BT piconet has been addressed by members of the IEEE 802.15 TG2 standards committee [4, 5]. In this paper, a more general analytical approach is presented. A methodology was developed for examining coexistence when there is uncertainty in the expected network traffic activity or uncertainty in the radio environment for the installation's operation.

Interference occurs when a packet from the interfering network is temporally and spectrally coincident with the desired signal and the interference signal has sufficient power to cause errors in recovering the desired signal. The methodology for the analysis centered on deriving a closed form solution for the probability of collision, $\Pr[C]$, in terms of the network and radio propagation parameters. A packet collision, C, was defined as the event where one or more interfering signals cause the desired service to retransmit a packet. In order to illustrate the approach, a stochastic model is derived to evaluate the impact of BT on IEEE 802.11b. A similar approach was used to evaluate the impact of IEEE 802.11b on BT as reported in [6]. A general approach for estimating the number of interfers is derived in Section 2. In Section 3, the derivation of $\Pr[C]$ is presented. In Section 4, an illustrative example is evaluated using the methodology presented and conclusions are given in Section 5.

2 Expected Number of Interfers

A method for determining the expected number of BT piconets, N_{BT}, having sufficient power to cause interference to an 802.11b station (STA), is derived. The

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derivation was based on first examining the relative received powers at the STA from both the desired signal source, 802.11b access point (AP), and BT piconets within radius D of the STA, Figure 1. Given the BT piconet are uniformly distributed with density D_{BT} piconets/m^2, then the expected number of BT piconets is

$$N_{BT}(\Gamma) = A_{eff}(\Gamma, d_S|D)\, D_{BT} \qquad (1)$$

where $A_{eff}(\Gamma, d_S|D)$ is the effective interference area given radius D. $A_{eff}(\cdot)$ estimates the area within a circle centered at the STA with radius D, where the interference signal from the BT piconets exceed the normalized interference to signal power ratio threshold, Γ. $A_{eff}(\cdot)$ is also dependent on the distance between the AP and the STA, d_S, where the dependency is governed by the radio propagation path loss characteristics. The normalized interference to signal power ratio threshold is given by

$$\Gamma = \gamma_{I/S} - \Omega_{BT} + \Omega_{AP} \ \text{(dB)} \qquad (2)$$

where Ω_{BT} and Ω_{AP} are the transmit powers in dBm for BT and 802.11b respectively and $\gamma_{I/S}$ is the interference to signal power threshold in dB, i.e., the threshold at which the interference signal corrupts the 802.11b transmission.

The effective interference area was determined using an approach similar to Jake's method [7] for determining the percentage of the useful coverage area within a cell's boundary when taking into account the effects of shadowing. That is

$$A_{eff}(\gamma_{I/S}, d_S|D) = \int_0^{2\pi}\int_0^{D} \Pr\left(\Omega_I(r)/\Omega_S(d_S) > \gamma_{I/S}\right) r\,dr\,d\theta \qquad (3)$$

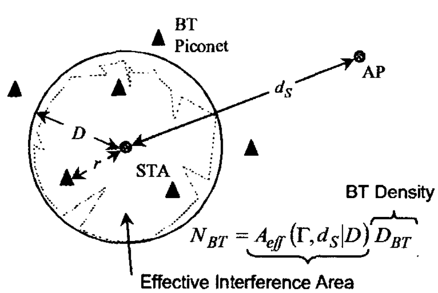

Figure 1 Geometry for analyzing effective interference area.

where $\Pr\left(\Omega_I(r)/\Omega_S(d_S) > \gamma_{I/S}\right)$ is the probability the interference power, $\Omega_I(r)$, at radius r, exceeds the received signal power from the STA, $\Omega_S(d_S)$, by $\gamma_{I/S}$. Both the signal power and interference power were based on a standard exponential decaying path loss model with path loss exponent, n, and with log-normal shadowing with standard deviations, σ_S and σ_I, respectively [8]. Assuming the log-normal distributed random variables (RVs) used to model the shadowing for both the interference and the desired signal are independent, then the interference to signal ratio is

$$\Omega_{I/S}(r, d_S) = \Omega_{BT} - \Omega_{AP} - 10n\log_{10}\left(\frac{r}{d_S}\right) - X_{I/S} \ \text{(dB)} \qquad (4)$$

where $X_{I/S}$ is a zero mean log-normal distributed RV with standard deviation $\sigma_{I/S} = \sqrt{\sigma_I^2 + \sigma_S^2}$. Using this formulation for $\Omega_{I/S}(r, d_S)$, (3) can be solved in a similar manner as the percentage coverage area as formulated in [8]

$$A_{eff}(\Gamma, d_S|D) = \frac{\pi D^2}{2}\left[1 - erf(a) + \exp\left(\frac{1-2ab}{b^2}\right)\left[1 - erf\left(\frac{1-ab}{b}\right)\right]\right] \qquad (5)$$

where $a = \left(\gamma_{I/S} - \overline{\Omega}_{I/S}(r, d_s)\right)/\sqrt{2}\,\sigma_{I/S} = \Gamma + 10n\log_{10}(r/d_s)$, $b = (10n\log_{10} e)/\sqrt{2}\,\sigma_{I/S}$ and $\overline{\Omega}_{I/S}(\cdot)$ is the mean of (4). By letting $D \to \infty$,

$$A_{eff}(\Gamma, d_S) = \lim_{D\to\infty} A_{eff}(\Gamma, d_S|D) = \pi\,(d_S)^2 \exp\left[\frac{2\left(\sigma_{I/S}^2 - 10n\Gamma\log_{10}(e)\right)}{(10n\log_{10}(e))^2}\right], \qquad (6)$$

the area is based on the BT piconets satisfying $\Omega_I(r)/\Omega_S(d_S) > \gamma_{I/S}$ regardless of D. Figure 2 contains graphs for $N_{BT}(\Gamma)/D_{BT} = A_{eff}(\Gamma, d_S)$, for typical operating conditions Γ=10 dB (i.e., Ω_{BT}= 0 dBm, Ω_{AP} = 20 dBm, $\gamma_{I/S}(0) = -10$ dB) and $0 < d_s \le 20\,m$.

3 Probability of Collision

Utilizing the results in Section 2, $\Pr[C]$ is derived in this section. Assuming the probability of activity, $\Pr[A_{BT}]$, is

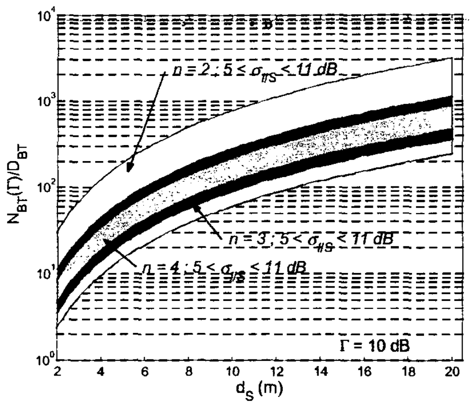

Figure 2 Normalized number of BT interfers exceeding interference versus d_S.

the same for each BT piconet and the activity at each piconet is independent of other piconet activity, then

$$\Pr[C] = \sum_{i=1}^{N_0} \binom{N_0}{i} (\Pr[A_{BT}])^i (1 - \Pr[A_{BT}])^{N_0 - i} \Pr[C_i] \quad (7)$$

where $N_0 \equiv round(N_{BT}(\hat{\Gamma}_0))$ is the expected number of BT interferers based on substituting (6) into (1) and $\hat{\Gamma}_0$ is a relative received power as discussed below. $\Pr[C_i]$ is the probability of at least one collision given i active piconets. The event C_i can be subdivided into L mutually exclusive events based on relative received power, $\hat{\Gamma}_q \; \forall q \in [0 \ldots L]$,

$$\Pr[C_i] = \sum_{q=1}^{L} \left(1 - \left(1 - \Pr\left[C_1 \middle| \hat{\Gamma}_q\right]\right)^i\right) \Pr\left[\hat{\Gamma}_q\right] \quad (8)$$

where $\Pr\left[\hat{\Gamma}_q\right]$ is the probability of $\hat{\Gamma}_q$ and $\Pr\left[C_1 \middle| \hat{\Gamma}_q\right]$ is the conditional probability of collision given a single active BT piconet with a given $\hat{\Gamma}_q$.

In order to evaluate $\Pr\left[C_1 \middle| \hat{\Gamma}_q\right]$, the likelihood a single piconet will be both time and frequency coincident with the 802.11b packet needs to be evaluated. Examining Figure 3, a dichotomy based on time coincidence is evident

$$\begin{aligned} \Pr\left[C_1 \middle| \hat{\Gamma}_q\right] &= \Pr[n_\tau] \; \Pr\left[C_1 \middle| n_\tau, \hat{\Gamma}_q\right] \\ &+ \Pr[n_\tau - 1] \; \Pr\left[C_1 \middle| n_\tau - 1, \hat{\Gamma}_q\right] \end{aligned} \quad (9)$$

where the 802.11b packet transmission is either time coincident with n_τ or $n_\tau - 1$ BT packets, i.e., time slots at different hopping frequencies. Assuming, the relative timing offset can be modeled as a uniform RV, $\tau_{offset} \in [0 \;\; T_{BT}]$, then it is straightforward to show that

$$n_\tau = \left\lceil \frac{T_P + \tau_{BT}}{T_{BT}} \right\rceil \quad (10)$$

where $\lceil \cdot \rceil$ is the ceiling function. The corresponding probabilities $\Pr[n_\tau]$ and $\Pr[n_\tau - 1]$ were obtained by evaluating τ_{offset} range corresponding to the event n_τ

$$\begin{aligned} \Pr[n_\tau] &= \frac{\tau_{BT} + T_P - (n_\tau - 1) T_{BT}}{T_{BT}} \\ \Pr[n_\tau - 1] &= 1 - \Pr[n_\tau] \, . \end{aligned} \quad (11)$$

In the analysis, it was assumed that if any portion of the 802.11b packet was time coincident with a BT transmission, then 802.11b packet retransmission is required, given frequency coincidence as discussed below. For the analysis presented in Section 4, the timing parameters were assigned typical values, $T_{BT} = 625\mu s$, $\tau_{BT} = 366\mu s$ and $T_P = 1210\mu s$.

From (9) and based on the derivation for n_τ,(10),

$$\Pr\left[C_1 \middle| n_\tau, \hat{\Gamma}_q\right] = 1 - \left(1 - L_{BT} \Pr\left[C_f \middle| \hat{\Gamma}_q\right]\right)^{n_\tau} \quad (12)$$

where BT time slots are equilikely and independently loaded and L_{BT} is the loading factor for the BT piconet, i.e., the fraction of the total number of BT time slots utilized. $\Pr\left[C_f \middle| \hat{\Gamma}_q\right]$ is the probability of the two WANs being frequency coincident given $\hat{\Gamma}_q$.

Based on empirical data [9, 10], the 802.11b can provide reliable service in the presence of narrow band

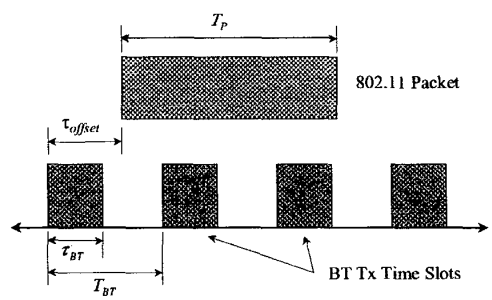

Figure 3 Relative packet timing.

interference occurring within its passband, given $\gamma_{I/S}(f_{offset}=0)<-10$ dB, where f_{offset} is the frequency offset between the two WANs carrier frequencies. The effect of varying f_{offset} was modeled by

$$\gamma_{I/S}(f_{offset})=\gamma_{I/S}(0)-J_S(f_{offset}) \text{ (dB)} \quad (13)$$

where $J_S(f_{offset})$ is the normalized jamming suppression of the 802.11b in the presence of BT interference. An analytical model of $J_S(f_{offset})$, based on a CW tone approximation, compares favorably to the results of an empirical study to evaluate $\gamma_{I/S}(f_{offset})$ [10].

Using the CW tone approximation for $J_S(f_{offset})$, a monotonic non-increasing function was used to estimate $J_S(f_{offset})$,

$$\hat{J}_S(f_{offset})=\max_{f\geq f_{q-1}}\left[J_S(f)\middle|\ f_{q-1}\leq f_{offset}<f_q\right] \quad ,(14)$$

where $f_q=qF_{step}$, F_{step} is the step size in MHz for the staircase estimation, $q\in[1\ldots L]$, and $L=\left\lfloor\frac{B_{BT}}{2F_{step}}\right\rfloor$. In Figure 4, $\hat{J}_S(f_{offset})$ is graphed with $F_{step}=5$ MHz. For the coexistence analysis presented in Section 4, $F_{step}=1$ MHz was used. Using (14) with (13) and substituting into (2), a quantized estimate for Γ based on frequency offset is obtained

$$\hat{\Gamma}(f_{offset})=\gamma_{I/S}(0)-\Omega_{BT}+\Omega_{AP}-\hat{J}_S(f_{offset}).(15)$$

Therefore, $\Pr\left[C_f\middle|\hat{\Gamma}_q\right]$, is based on evaluating the frequency range over which the BT signal can cause interference given $\hat{\Gamma}_q\equiv\hat{\Gamma}(f_{offset})\Big|_{f_{q-1}\leq f_{offset}<f_q}$, i.e.,

$$\Pr\left[C_f\middle|\hat{\Gamma}_q\right]=\frac{2qF_{step}}{B_{BT}}. \quad (16)$$

This assumes a worst case condition, when the 802.11b carrier frequency is centered within the UL band, such that the sidelobe interference can occur for both positive and negative carrier offsets, $|f_{offset}|<f_q$, for the BT interferer.

To complete the derivation of $\Pr[C]$, $\Pr\left[\hat{\Gamma}_q\right]$ needs to be evaluated. Based on (15) and (14), the L events $\hat{\Gamma}_q$ are

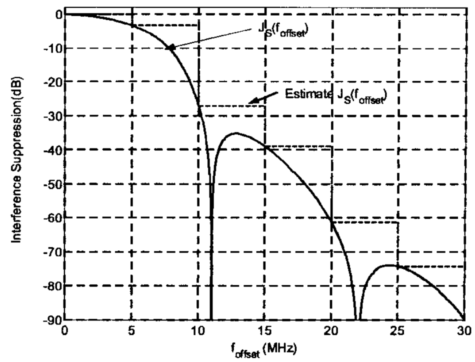

Figure 4 Jamming suppression versus carrier frequency offset.

mutually exclusive and $\sum_{q=1}^{L}\Pr\left[\hat{\Gamma}_q\right]\equiv 1$ given F_{step} is sufficiently small. $\Pr\left[\hat{\Gamma}_q\right]$ can be obtained by first noting $\hat{\Gamma}_q\geq\hat{\Gamma}_{q-1}\ \forall q\in[1\ldots L]$. Using (1), the corresponding expected number of BT piconets is also ordered, $N_{BT}(\hat{\Gamma}_q)\leq N_{BT}(\hat{\Gamma}_{q-1})$. The expected number of BT interfers with $\hat{\Gamma}_q$ can be estimated by $N_{BT}(\hat{\Gamma}_{q-1})-N_{BT}(\hat{\Gamma}_q)$. The probability of $\hat{\Gamma}_q$ is therefore

$$\Pr\left[\hat{\Gamma}_q\right]\approx\frac{A_{eff}(\hat{\Gamma}_{q-1},d_S)-A_{eff}(\hat{\Gamma}_q,d_S)}{A_{eff}(\hat{\Gamma}_0,d_S)} \quad (17)$$

where $\hat{\Gamma}_0=\hat{\Gamma}(0)=\Gamma(0)$, i.e., $\hat{\Gamma}(\cdot)$ or $\Gamma(\cdot)$ evaluated at $f_{offset}=0$.

4 Illustrative Example of Analytical Approach

There are essentially six independent variables associated with evaluating (7)

1) BT piconet parameters $\equiv[L_{BT}, D_{BT}, \Pr[A_{BT}]]$

2) Radio propagation parameters $\equiv[n, \sigma_{I/S}, d_S]$.

Fixing the radio propagation parameters $[n=3, \sigma_{I/S}=8\,\text{dB}, d_S=15\,\text{m}]$, then $\Pr[C]$ can be evaluated over the BT network parameters. The BT network parameters define a three dimensional volume. Curves of equal $\Pr[C]$ describe surfaces within the BT parameter space volume, as illustrated in Figure 5 for $\Pr[C]=0.2$.

Two specific BT piconet scenarios are also depicted in the figure: $\Delta_L \equiv$ light BT piconet scenario, and $\Delta_H \equiv$ heavy BT piconet scenario. For Δ_L, the average piconet traffic activity was based on 10 calls/day @ 2 min/call and 15 emails/day @ 10 kbytes/email. This scenario was based on a typical BT usage in an enterprise setting as reported in [5]. The piconets were uniformly distributed with 0.04 piconets/m^2. For Δ_H, traffic consisted of 10 calls/day @ 2 min/call and 20 Mbytes/day data (email, printer, etc.) and with 0.08 piconets/m^2. The two BT piconet scenarios, Δ_L and Δ_H, represent points in the BT piconet parameter space with $\Pr[C]|_{\Delta_L} \approx 0.07$ and $\Pr[C]|_{\Delta_H} \approx 0.34$.

The effect of radio propagation parameter variation was investigated by fixing the BT network parameters at both Δ_L and Δ_H. Graphs (a) and (b) in Figure 6 depict $\Pr[C]$ for variations in the radio propagation parameters.

5 Conclusions

In this paper, a closed form analytical model was derived for evaluating the impact of BT on 802.11b. The approach is illustrated by examining the coexistence between 802.11b and BT within typical operational ranges for both network traffic and RF environments.

6 References

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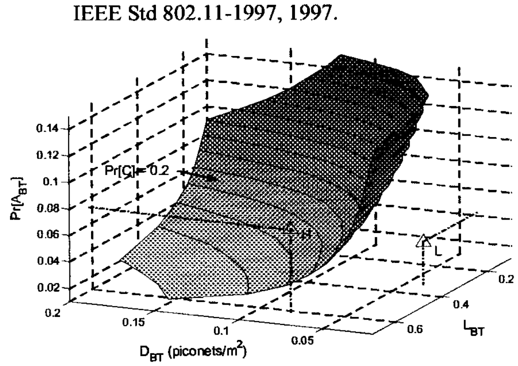

Figure 5 $\Pr[C]=0.2$ over BT network parameters ($n=3$, $\sigma_{I/S}=8\,dB$ and $d_S=15m$).

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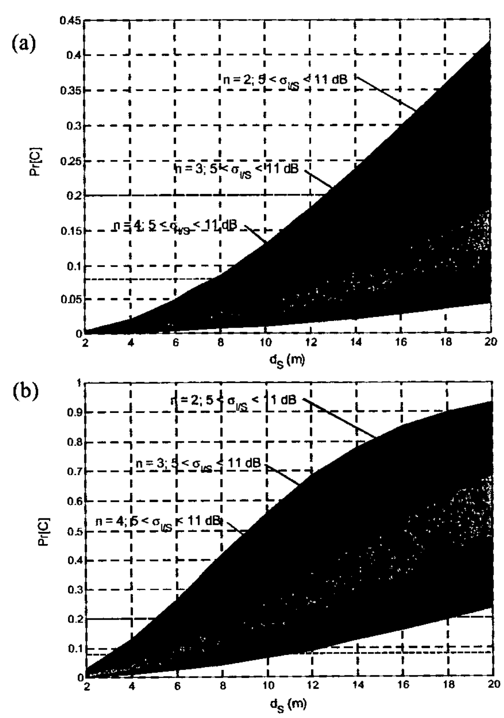

Figure 6 $\Pr[C]$ versus d_S for (a) $\Delta_L \equiv$ light BT network, (b) $\Delta_H \equiv$ heavy BT network.