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Energy-Based Analysis of Interfering IEEE 802.11b and Bluetooth Networks

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ABSTRACT

The increasing use of unlicensed frequency bands for wireless data communications calls for detailed investigations of the potential interference problems. In this paper we analyze coexisting IEEE 802.11b and Bluetooth networks with respect to throughput using a framework that allows for multiple packet lengths to be used by the communicating devices. The analysis is performed with respect to the received interfering energy, which in effect leads to a link budget analysis on a packet basis. The results indicate that the adjacent channel interference has a great impact on the performance of interfering Bluetooth networks when the distance to the interferers is small. Furthermore, it is indicated that the performance of Bluetooth networks in the vicinity of interfering IEEE 802.11b networks is not strongly dependent on the distance to the interferers.

INTRODUCTION

The use of unlicensed frequency bands for personal data communications has been increasing for some time. E.g., wireless local area networks (WLANs) are commonly deployed in home and office environments, and wireless personal area networks (WPANs) are used for data cable replacements in a wide variety of consumer products. As the numbers of devices sharing the unlicensed bands and the traffic in the networks increase, reduced performance, e.g., in terms of data rate, due to higher levels of interference in the bands, may become a problem (Figure 1).

To address some of these coexistence problems, specifically in the unlicensed industrial, scientific and medical (ISM) band at 2.4 GHz, recent work has been focused on the coexistence of WLANs based on different versions of the IEEE 802.11 standard and WPANs based on the Bluetooth standard. E.g., in [1] the coexistence of multiple Bluetooth networks is analyzed with respect to packet collisions, but the analysis is limited to networks using a single packet length. The extension to the case where the networks use different lengths of the transmitted packets is treated in [2]. In [3] a more detailed analysis is performed, considering radio link properties and adjacent channel interference etc., but limited to a single packet length. A similar approach to the one used in [3] is used in [4] to analyze the coexistence of Bluetooth and IEEE 802.11b, which is also done in a detailed way in [5]. However, the focus on modelling the interfering networks, specifically the radio links, in great detail in [4] and [5], makes general conclusions about the network performance hard to draw. Therefore, in this paper we analyze Bluetooth and IEEE 802.11b networks using a previously derived self-contained analytical framework for the analysis of interfering packet radio networks. By effectively performing a link budget analysis on a packet basis, including the adjacent channel interference we will on one hand hide some of the radio link details, but on the other hand take the interference mechanisms related to the use of multiple packet lengths into account, which has not been done before.

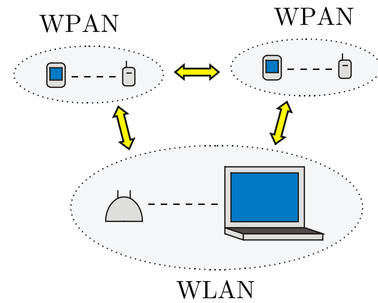

Figure 1: Interference indicated by arrows between wireless communication networks sharing the same frequency bands.

ANALYSIS

The system model that we will use is a somewhat modified version of the system model presented in detail in [6], which in part has been used in previous publications [2,7]. The systems analyzed consist of a collection of networks with units that communicate by transmitting packets. The networks are assumed to be 'unaware' of each other, which means that they sometimes interfere by transmitting packets simultaneously in the same or partly overlapping frequency bands.

Each network in the system has a set of available packet types that can be used for packet transmissions. The packets can have different lengths, carry different amounts of data and can have different robustness properties against interference.

As a measure of network performance we will use the ensemble average network throughput in the analysis, which can be associated with the data transfer rate of the networks. Based on the throughput expression, the analysis consists of calculating the successful packet reception probability for all packet types used.

The successful packet reception probability will depend on what is assumed to cause packet losses in the system, and in this paper we will make the assumption that the outcome of packet receptions is determined by the signal to noise and interference ratio (SNIR) at the receiver of the packets. We will in effect perform a link budget analysis on a packet basis, which allows for distance, transmitted power and receiver sensitivities to be accounted for to some extent.

By considering only fixed distances between all network units and no fading, the received useful power C at a receiver is a fixed deterministic quantity given by the transmitted useful power, the distance attenuation and perhaps some additional losses at the receiver. In addition we will assume that the receiver noise is given by the deterministic noise power parameter N_{noise}. Consequently, the minimum tolerable SNIR, γ_{min}, can be translated into a maximum tolerable received interfering energy $E_{I,max}$ received during the packet reception.

To find the probability of successful packet reception, we will calculate the probability distribution function (PDF) of the received interfering energy received during the reception of a reference packet, and then integrate over the PDF from zero up to the threshold $E_{I,max}$ for the maximum amount of interference that can be tolerated. Note that this includes taking all possible overlaps in time into account, as well as the power leakage between all pairs of channels that can be used. How this is done is described in detail in [6] and is not included in this paper due to space limitations.

To summarize, the method of analysis consists of the following steps: To calculate the throughput of a network the probabilities for successful receptions of the packet types used by the network must first be determined. This is done by examining the interference received during the reception of the packets, i.e., by calculating and integrating over the PDFs of the total received interference for each packet type. The PDF of the total received interference is in turn obtained by convolution of the PDFs of the interference received from all the individual interfering networks in the system since all interferers are assumed to be transmitting independently.

NETWORK MODELING

Using the system model and the method of analysis described in [6] we will now engage in an analysis of a system consisting of a collection of IEEE 802.11b and Bluetooth networks. To be able to perform the analysis we must first determine appropriate system model parameters. Starting with Bluetooth, three of the packet types defined in the standard [8] will be used, namely DH1, DH3 and DH5. We will assume that they are equally probable of being selected for transmissions within the Bluetooth networks. Thus, we have

Packet selection prob.	r =	[1/3 1/3 1/3]
Header length	h =	[150 158 158] µs
Guard interval length	d =	[275 269 271] µs
Packet duration	L =	[625 1875 3125] µs
Payload bit rate	D =	[1 1 1] bits/µs,

and a channel set consisting of 79 channels with all channels equally probable of being selected. The Bluetooth networks use packet-based frequency hopping over the channels in the channel set, which means that there is a pseudo-random change of channel after each packet transmission.

The link budget for the Bluetooth networks will be assumed to be given by

Radiated power	EIRP =	8 dBm
Path loss (ref. units)	$L_{PL,ref}$ =	4 dB
Path loss (interf. units)	$L_{PL,interf}$ =	[4 18 24] dB
Receiver loss	L_r =	2 dB
Min. received SNIR	γ_{min} =	20 dB,

where the path loss figures 4, 18 and 24 dB corresponds to free-space path loss for distances of 1, 5 and 10 meters at 2.4 GHz. We have assumed a transmit power of 10 dBm and transmitter losses of 2 dB to obtain an effective isotropically radiated power (EIRP) of 8 dBm. The propagation loss between the units of the reference network has been set to 4 dB which corresponds to a distance of approximately 1 m. In the calculations below we will consider three scenarios where the distances between the units of the reference network and the units of the interfering networks are either 1, 5 or 10 meters.

To find the parameter $E_{I,max}$, we will assume that the Bluetooth receivers in the system are characterized by the parameters

Noise figure	F_{sys} =	20 dB
Noise bandwidth	B =	60 dBHz
Ref. noise pow. dens.	N_0 =	-174 dBm/Hz,

which results in a noise power of

$$N_{\text{noise}} = F_{\text{sys}} + B + N_0 = -96 \text{ dBm}. \quad (1)$$

It should be noted that current Bluetooth receiver implementations generally have lower noise figures than 20 dB. For successful packet reception, the received SNIR must be above the specified threshold γ_{min}, which means that

$$\frac{C}{N_{\text{noise}} + E_I/(L-d)} > \gamma_{\min} \quad (2)$$

must be fulfilled, where the parameters are all in a linear scale. With these figures, the thresholds for the amount of tolerable interfering energy, for each of the three Bluetooth packet types are

$E_{I,max}$ = [5.55 25.5 45.2] nJ.

The IEEE 802.11b networks [9,10] use a single wideband carrier in the ISM-band and no frequency hopping. Consequently, we define the channel set used by the IEEE 802.11b networks to consist of only one channel. We will assume that the 11 Mb/s mode of transmission is used for transmitting packets of three different packet lengths which are equally likely to be selected. The carrier sense multiple access mechanism with collision avoidance (CSMA/CA) cannot be modelled in detail using the system model presented, since it introduces dependencies between packet transmissions. We will simply assume that there are no collisions within an IEEE 802.11b network and that all packets transmitted are separated in time by 50 µs (corresponding to a DIFS interval). With short preambles the headers are all 96 µs , and with payloads of 40, 500 and 1500 bytes, the packet durations become approximately 96+30+50, 96+364+50 and 96+1091+50 µs . Thus,

Packet selection prob.	r =	[1/3 1/3 1/3]
Header length	h =	[96 96 96] µs
Guard interval length	d =	[50 50 50] µs
Packet duration	L =	[176 510 1237] µs
Payload bit rate	D =	[11 11 11] bits/µs.

The IEEE 802.11b link budget will be given by

Radiated power	EIRP =	23 dBm
Path loss (ref. units)	$L_{PL,ref}$ =	24 dB
Path loss (interf. units)	$L_{PL,interf}$ =	[4 18 24] dB
Receiver loss	L_r =	2 dB
Min. received SNIR	γ_{min} =	10 dB.

Here we have assumed an EIRP of 200 mW. The propagation loss between the units of the reference network has been set to 24 dB corresponding to a distance of approximately 10 m.

The IEEE 802.11b receivers are assumed to be characterized by the parameters

Noise figure	F_{sys} =	7 dB
Noise bandwidth	B =	74 dBHz
Ref. noise pow. dens.	N_0 =	-174 dBm/Hz,

which results in a noise power of

$$N_{\text{noise}} = \text{-93 dBm}. \quad (3)$$

From (2), the thresholds for the amount of tolerable interfering energy for the three packet lengths used by the IEEE 802.11b networks are

$E_{I,max}$ = [6.32 23.1 59.5] nJ.

Lastly, to get an estimate of the performance in the worst case interference situation, we will use very simple models of the transmit power spectra and the receiver channel selectivities of the Bluetooth and IEEE 802.11b transmitters and receivers. The transmit power spectra and receiver channel selectivities used are shown in Figure 2, and they roughly correspond to what is given in the specifications.

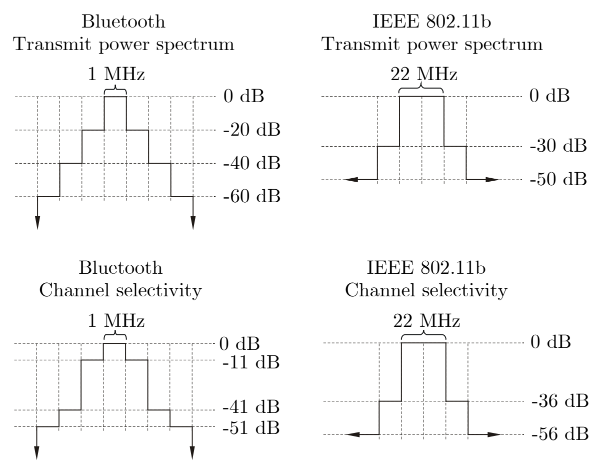

Figure 2: Models of Bluetooth and IEEE 802.11b transmit power spectra and receiver channel selectivities.

It should be noted that the assumption about no internal interference within networks is generally not valid in the IEEE 802.11b case, but we will neglect the packet losses due to internal packet collisions within the networks.

BLUETOOTH PERFORMANCE

We start by analyzing a single Bluetooth reference network in the vicinity of other interfering Bluetooth networks. To do this, we must first calculate the adjacent channel attenuation factors between all pairs of channels in the system using the transmit power spectrum and the receiver channel selectivity displayed in Figure 2. Different channel selections by transmitter and receiver will give rise to different amounts of attenuation of the received interference depending on the relative difference in frequency of the carriers. E.g., if the channel selected by the interferer is the second neighbor to the channel selected by the reference network, we have the situation shown in Figure 3.

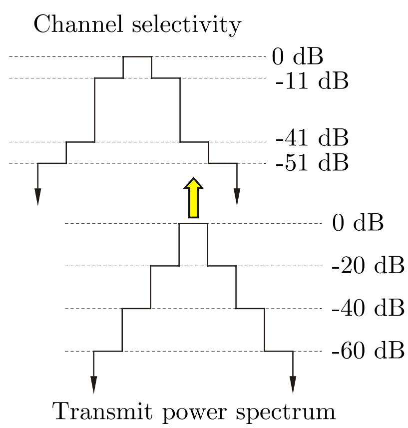

Figure 3: Channel selectivity for a Bluetooth reference network and the transmit power spectrum for an interfering Bluetooth transmitter. The selected channel for the interfering transmission relative to the reference network transmission is indicated by the arrow.

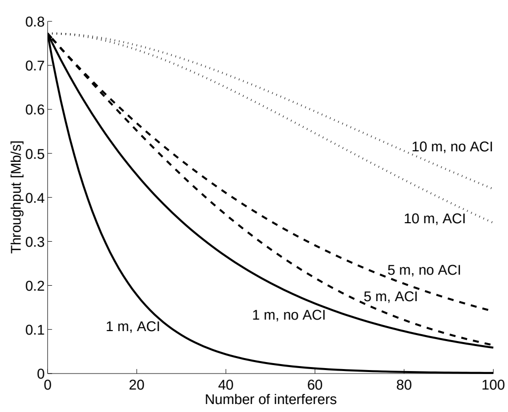

Figure 4: Bluetooth throughput as a function of number of interfering Bluetooth piconets in the system. Distance between reference network units and interfering network units is either 1 m (solid curves), 5 m (dashed) or 10 m (dotted). For each distance two curves are shown representing results with and without ACI.

Consequently, there will be leakage of power through the overlapping regions of the power spectra and the channel selectivity masks, and the leakage will influence the PDFs of the total received interfering energy.

By calculating the PDFs of the total received interfering energy received during packet receptions, and then the throughput for the reference network as a function of number of interfering networks, we obtain the lower-most solid, dashed and dotted curves in Figure 4.

As indicated by the labels in the figure, results for the case when there is no ACI has also been included. The solid, dashed and dotted curves are results for the cases where the distances between reference network units and interfering network units are either 1, 5 or 10 m.

It can be seen that the ACI has a significant impact on the throughput when the interferers are close to the reference network units. Since the worst case ACI has been used in the analysis, it can be expected that the throughput for real system setups ends up somewhere inbetween the curves with and without ACI. Furthermore, it should be noted that even though results are shown for number of interferers up to 100 networks, more than 40 interfering networks with distances below 10 m between each other are currently an unlikely scenario.

Next, we consider a Bluetooth reference network in the vicinity of interfering IEEE 802.11b networks. The throughput results from the calculations are shown in Figure 5 as a function of number of interfering IEEE 802.11b networks for different distances to the Bluetooth reference network.

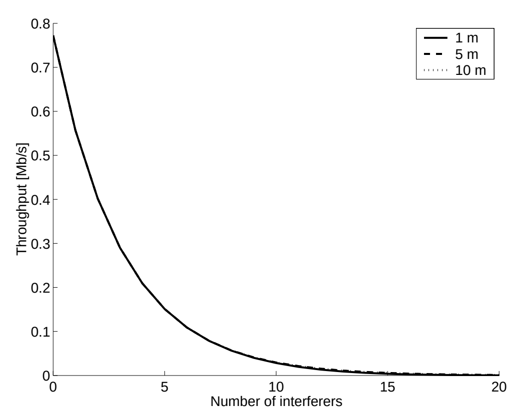

Figure 5: Throughput of a Bluetooth reference network as a function of number of interfering IEEE 802.11b networks for distances of 1, 5 and 10 m between

reference network units and interferers. The curves overlap almost completely.

As can be seen in the figure the three curves for 1, 5 and 10 m distances overlap almost completely. Consequently, the distance to the interferers does not matter in this case. Note that results are shown for numbers of networks up to 20 in this figure, which is currently a high number of IEEE 802.11b networks deployed in such a limited area.

IEEE 802.11B PERFORMANCE

To analyze the performance of an IEEE 802.11b reference network in the vicinity of interfering Bluetooth networks we use the same method as in the previous section. In Figure 6, the throughput of an IEEE 802.11b network has been plotted as a function of number of interfering Bluetooth networks for distances between reference and interfering units of 1, 5 and 10 m.

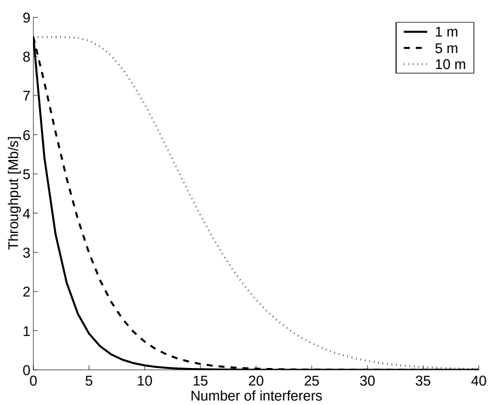

Figure 6: IEEE 802.11b network throughput as a function of number of interfering Bluetooth networks. Results are shown for distances between reference network and interfering network units of 1 (solid curve), 5 (dashed) and 10 m (dotted).

It can be seen in the figure that when the Bluetooth networks are close to the IEEE 802.11b reference network, network throughput decreases rapidly with the number of interferers.

CONCLUSIONS

A system of coexisting IEEE 802.11b and Bluetooth networks has been analyzed with respect to throughput. The framework used in the analysis is based on the interfering energy received during packet receptions, and the system model allows for different packet lengths to be used by the network units.

The results from the analysis indicate that the ACI has a strong impact on the performance of interfering Bluetooth networks when the separation distance is small. It was also indicated that the performance of Bluetooth networks in the environment of interfering IEEE 802.11b networks is only weakly dependent on the distance to the interferers.

As a future work item it is suggested that the validity of the energy-based method of analysis is investigated. In addition, since fixed sets of packet types were used in the analysis, future investigations could focus on different packet sets and the corresponding impact on the performance of the networks.

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