Channel Frame Error Rate for Bluetooth in the Presence of Microwave Ovens

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Abstract— **In this paper, radiation from microwave ovens is measured using PRISM, a custom-built device designed to measure transmissions in the ISM band. The measured signals, treated as a rising noise floor, are then applied to a semi-analytic simulation to determine the probability of frame error rate (FER) per channel for six Bluetooth packet types [1].**

Keywords—*Bluetooth; ISM band; Microwave ovens; Frame error rate*

I. INTRODUCTION

Bluetooth is a wireless technology using FH-CDMA/TDD for providing short-range connectivity. Bluetooth radio operates in the 2400-2483.5 MHz frequency band, also known as the ISM (Industrial Scientific and Medical) band, a license free band allocated for a variety of consumer applications. While no license needs to be purchased to operate devices in this band, it is regulated. Part 15 of the FCC code limits the output power, channel bandwidth and air interface of wireless devices operating in the ISM band. However, devices such as microwave ovens that also operate in and around this band are regulated by a different set of restrictions than communications systems. Since 1971 the Center for Devices and Radiological Health (CDRH), a part of the U.S. Food and Drug Administration (FDA) has been responsible for regulating radiation emanating from microwave ovens. Since the primary objective of a microwave oven is to heat or cook food, these regulations address heath concerns. Therefore, the energy radiated by a microwave oven could have a significant impact on a communications link using the same spectrum as Bluetooth. In this paper, we evaluate the effect of microwave ovens on the performance of Bluetooth systems. Data collected to characterize the radiation from a microwave oven is applied to a semi-analytic simulation of various Bluetooth packet transmissions [1], to provide an estimate of the expected frame error rate (FER) per channel of a series of Bluetooth links using six different types of packets (DM1, DM3, DM5, DH1, DH3, DH5).

These packets are used for Asynchronous Connectionless Links (ACL, primarily data) and use ARQ. The remainder of this paper is organized as follows: In Section II basic features of Bluetooth pertaining to this study are discussed. In Section III the probability of retransmission is given from [2], which is used to estimate the FER for Bluetooth in the presence of microwave ovens. In Section IV the measurement system, PRISM is described and the test scenario is presented. Frame error rate results are given for six ACL packet types as a function of 79 Bluetooth channels.

II. FEATURES OF BLUETOOTH

Bluetooth uses frequency-hopping spread spectrum (FHSS) technology. The frequency band over which Bluetooth operates is divided into 79 1-MHz channels between 2400 and 2483.5 MHz. Bluetooth has a hop rate of 1600 hops per second, where each channel is generally used in 625 µs slots. Bluetooth uses Gaussian frequency shift keying (GFSK) modulation with a time-bandwidth product BT = 0.5, modulation index $0.28 \leq h \leq 0.35$ and a modulation symbol rate of 1 Mb/s. Full duplex transmission capability is achieved using time division duplexing (TDD), where subsequent slots are used for transmitting and receiving. Bluetooth is organized into a Master-Slave architecture, where Master devices transmit in even-indexed time slots and slave devices transmit in odd-indexed slots. An ACL packet may occupy 1, 3, or 5 consecutive slots, hence a packet may occupy a channel for periods longer than 625 µs. Bluetooth packets consist of a 72-bit access code for piconet identification and synchronization, a 18 bit header (54 bits gross due to triple redundancy), and a variable length payload. The payload consists of three segments: a payload header, a payload and a 16 bit CRC for error detection. In DMx packets, the payload is FEC coded with (15, 10) shortened Hamming code, while the DHx packets are uncoded. Table 1 gives brief overview of the packets.

TABLE I.ACL PACKET TYPES IN BLUETOOTH

Packet Type	Slots, Payload Header and Data Bytes	Encoding	Total Bits
DM1	1 slot, 1 byte payload header, 17 bytes of data	2/3 FEC	240
DM3	3 slots, 2 byte payload header, 121 bytes of data	2/3 FEC	1500
DM5	5 slots, 2 byte payload header, 224 bytes of data	2/3 FEC	2745
DH1	1 slot, 1 byte payload header, 27 bytes of data	No FEC	240
DH3	3 slots, 2 byte payload header, 183 bytes of data	No FEC	1496
DH5	5 slots, 2 byte payload header, 339 bytes of data	No FEC	2744

III. PROBABAILTY OF RETRANSMISSION

The probability of retransmission by a Bluetooth receiver is given by [2]:

$$P_r(\gamma) = 1 - P[\overline{A}]P[\overline{B}]P[\overline{C}]P[\overline{D}]P[\overline{E}], \quad (1)$$

where A, B, C, D, and E are the events:

A: the 72-bit synchronization of the forward channel fails.

B: the header FEC of the forward channel fails.

C: the Hamming code protecting the payload of the forward transmission fails.

D: the 72-bit synchronization of the reverse packet fails.

E: the header FEC of the reverse channel fails.

$P_r(\gamma)$ is evaluated for $\gamma = \{\gamma_f, \gamma_r\}$, which contains the instantaneous forward and reverse signal-to-noise ratios. Using the analysis for probability of retransmission presented in [2], the FER of each packet type as a function of the channel interference level can be calculated.

IV. MEASUREMENT SYSTEM

PRISM (PRobe ISM) is an automated passive measurements device whose center frequency is placed at 2.45 GHz. Using PRISM, microwave oven emissions were measured.

Figure 1 shows a block diagram of PRISM. PRISM consists of a vertical dipole sleeve antenna that is in connected through a LNA to a Hewlett-Packard (8594E) spectrum analyzer. The LNA has a noise figure of 1.5 dB and a gain of 30 dB, enabling the system to measure weak signals. Finally, the spectrum analyzer is connected to the PC through a GPIB interface.

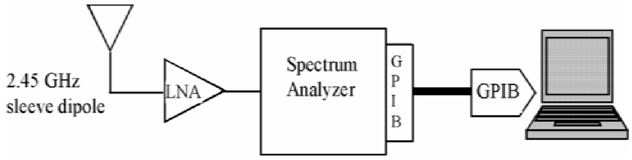

Figure 1. System Model of PRISM .

The PRISM software was developed in LabView, which is used to easily control the system settings and perform data logging. Post processing of data collected through PRISM is performed in MATLAB, which provides an extensive tool set for data analysis and visualization.

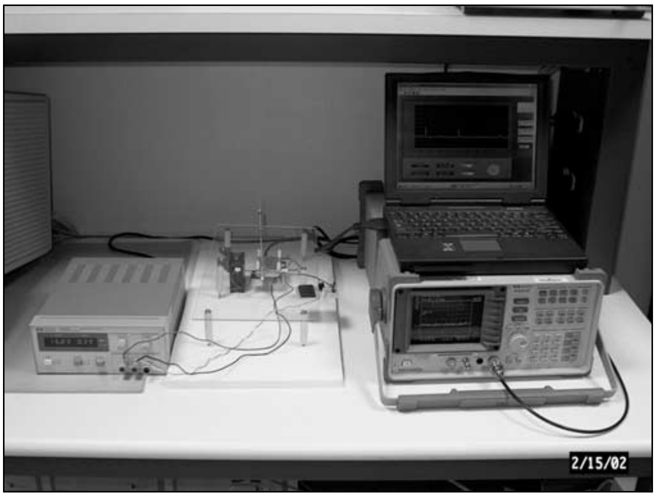

Figure 2. PRISM.

Line of sight measurements were performed in an office environment with a microwave oven heating a cup of water. The radiation from the microwave oven was recorded using PRISM at varying distances (5-30 feet) over a period of two minutes. Two microwave ovens of different make (Microwave Oven I: Panasonic, Model NN-7553A, 1994; Microwave Oven II: GE, Model JES1131GB001, 1999) were used independently for the study.

V. INTERFERENCE ANALYSIS

In order to estimate the performance of Bluetooth devices in the presence of microwave ovens, data was first collected on the radiation emitted by a set of microwave ovens. Figure 3 shows the power radiated by Microwave Oven I at a distance of 10 feet as a function of frequency and time. The collected data was collapsed into minimum, maximum and average interference vectors covering the channel set. Figures 4 and 5 show the interference measured at each individual Bluetooth channel when Microwave Oven I is placed a distance of 10 feet and 20 feet from the measurement equipment, respectively.

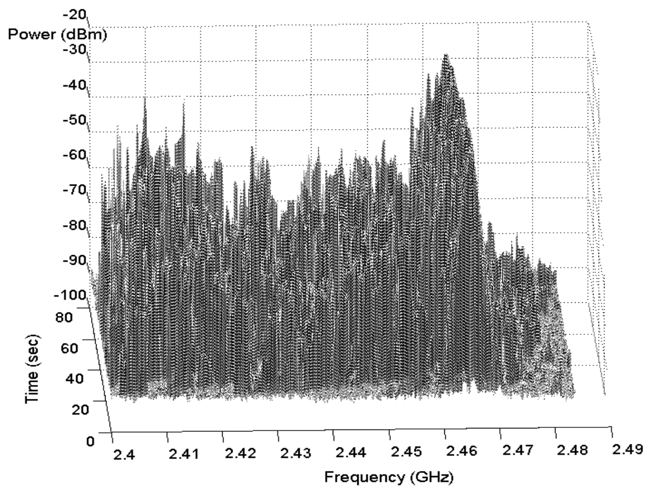

Figure 3. Interference received 10 feet away from Microwave Oven I as function of frequency and time.

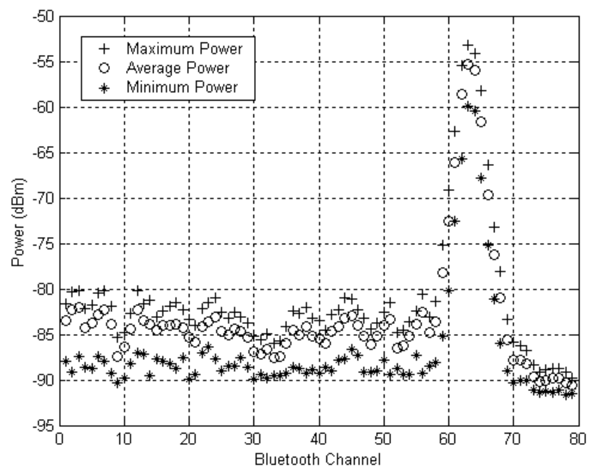

Figure 4. Interference experienced by each indvidual Bluetooth Channel when the receiver is 10 feet away from Microwave Oven I.

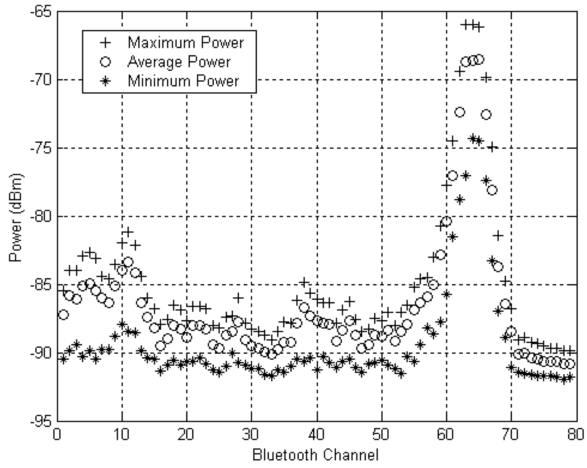

Figure 5. Interference experienced by each indvidual Bluetooth Channel when the receiver is 20 feet away from Microwave Oven I.

The Bluetooth standard requires a receiver sensitivity of -70dBm for a raw BER (Bit Error Rate) of 0.1% [1]. Using this threshold, the device's allowable noise floor can be calculated. By treating the power radiated from the microwave oven as non-coherent noise, the frame error rate was estimated for the six types of Bluetooth packets based on the probability of retransmission derived in [2]. Figures 6 and 7 show the expected FER for each of these packet types when Microwave Oven I is operating 10 feet and 20 feet away from the receiver.

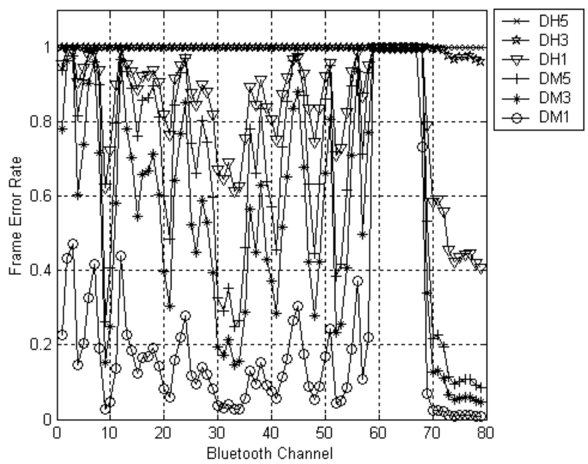

Figure 6. FER for the six ACL packet when the receiver is 10 feet away from Microwave Oven I.

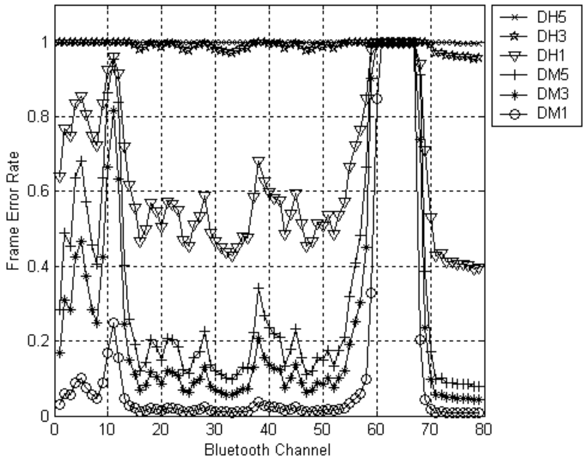

Figure 7. FER for the six ACL packet when the receiver is 20 feet away from Microwave Oven I.

As seen in Figure 7, there is a dramatic difference in the expected performance between different packets, with DMx packets showing consistently lower FER than DHx packets, and Dx1 packets showing lower FER than Dx3 packets, which in turn show low FER than Dx5 packets. The experiment was performed over a distance of 30 feet. A gradual improvement in FER was noted as the receiver was moved away from the microwave oven.

Another set of experiments was performed for Microwave Oven II under identical conditions. Figures 8 and 9 show the channel interference and FER obtained 10 feet away from Microwave Oven II. As seen in Figure 8, there is some variation in the amount of interference observed in each channel when compared to the interference measured from Microwave Oven I. However, one common aspect of both sets of measurement is that channels 60 through 70 were subjected to high interference from both microwave ovens.

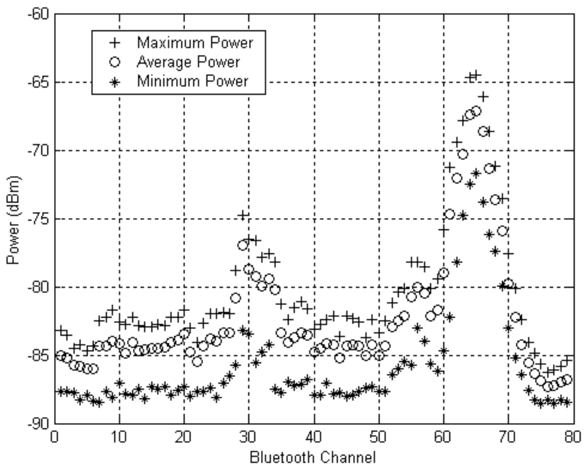

Figure 8. Interference experienced by each indvidual Bluetooth Channel when the receiver is 10 feet away from Microwave Oven II.

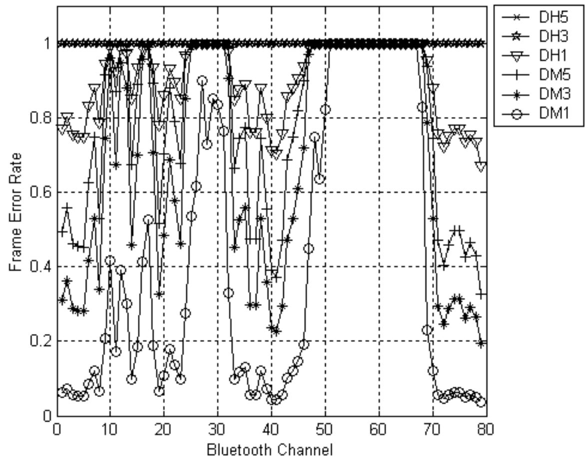

Figure 9. FER for the six ACL packet when the receiver is 10 feet away from Microwave Oven II.

When comparing Figures 7 and 9, some aspects of system performance are evident. In both scenarios, it is evident that, when a microwave oven is operating, the probability of frame error indicates that DHx packets have a very limited utility, while DMx packets, especially DM1 and DM3, can consistently operate effectively. Furthermore, it is evident that several channels are subject to such levels of interference that any communication over those channels should be impossible.

It should be noted that, while some similarities between the systems measured are evident, this investigation is not exhaustive, and a definitive set of rules that apply to all microwave ovens cannot be defined.

VI. Conclusion

PRISM is an effective system for measuring and studying EMI in the ISM band. Interference in the ISM band inherent to microwave ovens was recorded. An estimate of the degradation of performance for Bluetooth systems due to microwave oven interference was created by treating the radiation from the microwave as non-coherent noise and applying it to the results for FER in [2]. While microwave ovens are regulated, it was shown that, for the systems measured, the level of interference can be significant. However, if the packet type used is selected judiciously, it should be possible for Bluetooth devices to operate in the environment measured.

Acknowledgment

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