THE PERFORMANCE OF BLUETOOTH™ TRANSMISSIONS IN ELECTROMAGNETIC INTERFERENCE ENVIRONMENT

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Abstract

A systematic analysis is presented to calculate the packet-loss probability in the Bluetooth™ transmissions impaired by Electromagnetic Interference (EMI) from the 3rd harmonic of 800 MHz mobile phone. Considerations of GFSK modulation adopted are duly taken into account. The effects of EM radiation from the 3rd harmonic of 800 MHz mobile phone in the transmission mode on the relevant performance impairment are determined. Simulation studies on Bluetooth™ communications consistent with the available details pertinent to EMI from the mobile phone are presented, and relevant conclusions on the interference involved are elucidated.

Key words: Bluetooth, EMI, Frame-Error-Rate

1. INTRODUCTION

In this research, the analysis will concentrate on the EM radiation of 800 MHz mobile phone because, at the 3rd harmonic of 800 MHz, the frequency component is located on the operating frequency range of Bluetooth™ system. From the previous research, a major implication in the deployment of Bluetooth™ transmissions is the EMI that could arise as a result of microwave leakage from the ovens operating in the vicinity of active Bluetooth-enabled devices [1]. However, addressed here is an analysis to evaluate the relevant impairments to the wireless transmissions involved and to deduce the loss in throughput efficiency that an operating Bluetooth™ system may suffer as a result of EM radiation from the 3rd harmonic of 800 MHz mobile phone operating in the same range.
The Bluetooth™ technology allows any electronic appliance to communicate with other(s) via 2.4 GHz ISM radio-frequency (RF) band over a short range. By sharing a channel by two or more Bluetooth-enable devices, a piconet is confounded in which one device acts as the master and other unit(s) serve as slave(s). The associated transmission could be either point-to-point basis (when only two Bluetooth™ units are involved) or point-to-multipoint connection (if more than 2 Bluetooth™ units participate). Further, a topology of multiple piconets with overlapping (coverage) areas without interfering to each other is also possible and it constitutes a scatternet.

The operation in these Bluetooth™ network configurations is based on frequency hopping technique, which assigns a unique sequence for each piconet. In order to combat, the interference from any neighboring piconet, a frequency hop-selection is adopted. That is, a set of (random) carrier frequencies are selected (in the assigned band), and the transmission of packets are supported on these frequencies, hopped randomly for each transmission. The pattern of frequency hopping is calculated using the address pertinent to the master. (This ensures only one unit being the master for each piconet, and clocks the transmission events.) There are 10 frequency sequences-five for the 79-hop system (used in the United States, Europe and most of other countries) and five for the 23-hop system (used in Japan, Spain and France, these countries, however, are expected to adopt the 79-hop system in near future.) The selection scheme consists of two parts: (i) Selecting a sequence and (ii) mapping this sequence on the hop frequencies. The general block diagram of the hop-selection scheme is shown in Fig. 1, where the mapping from the input to a particular hop frequency is performed in the selection box.

![Fig.1: Hop selection scheme based on Master's address](image)

The prescribed hop rate is 1600 hop/second so that the duration spanning each hop is 625 µs. In this time period, the bit-data are transmitted with the corresponding sequence of channels adopted being in pseudorandom from. Both transmitter and receiver use the same pseudo code to tune into the sequence of channel clocked to synchronization.

A typical block diagram of a Bluetooth™ radio using frequency-hopping and GFSK modulation is illustrated in Fig. 2.
In transmission mode, the binary data are fed into a modulator that uses the GFSK scheme. The resulting modulation is centered around some base frequency. Next, the selected frequency from the hop-selection box is modulated with the output signal from the GFSK modulator so as to shift the signal to be centered around the selected hop frequency. On the receiver side, the frequency-hopped spread-spectrum signal is pre-demodulated using the same hop-frequency used at the transmitter and then subjected to BFSK demodulation. Hence, the binary data is recovered at the final output.

2. ERROR PROBABILITY FOR GFSK
Due to the Bluetooth\textsuperscript{TM} radio chip uses the GFSK modulation with modulation index between 0.28 and 0.35 for balancing the effect of in-band interference between bit “0” and bit “1” and 0.5 $WT_b$ factor on gaussian filter. The GFSK is almost similar to FSK modulation. The differences, however, between the two lie in the implementation considerations. The GFSK modulator is identical to a FSK modulator except that, before the baseband pulse goes into the FSK modulator, it is passed through a Gaussian filter. This makes the pulse shaped so as to limit its spectral width. Desirably, this pulse shaping filter should satisfy the following properties: Frequency responses with narrow bandwidth and sharp cutoff characteristics, which would suppress the high-frequency components of the transmitted signal; and, an impulse response with relatively low overshoot to avoid excessive deviations in the instantaneous frequency of the FM signal.

Hence the response $g(t)$ of this filter is specified by a Gaussian transfer function. In reference to a rectangular pulse of unit amplitude and duration $T_b$ (centered on the origin), $g(t)$ is given by:

$$
g(t) = \frac{1}{2} \left[ \text{erfc} \left( \pi \frac{2}{\log 2} WT_b \left( \frac{t}{T_b} - \frac{1}{2} \right) \right) - \text{erfc} \left( \pi \frac{2}{\log 2} WT_b \left( \frac{t}{T_b} + \frac{1}{2} \right) \right) \right]$$

(1)

**Fig. 3: Frequency-shaping pulse $g(t)$ from equation 1 for varying $WT_b$**
In essence, this pulse response enables a frequency shaping of a rectangular pulse at the GMSK modulator, with the (dimensionless) time-bandwidth product WT_b playing the role of a design parameter; as illustrated in Fig. 3.

From Fig. 3, it can be observed that a rectangular through a gaussian filter spreads out so that the bit duration time (-T_b/2 to T_b/2), meaning that the bit energy bounded between -T_b/2 to T_b/2, spreads out of that specified bound. Hence, while determining the signal energy, the signal should be limited the time boundary as necessary. A degradation factor (ν) can be defined as the ratio between the energy from output gaussian filter between -T_b/2 to T_b/2 and the original bit energy of the rectangular pulse, as follows:

$$\nu = \frac{\int_{-T_b/2}^{T_b/2} g(t) dt}{E_b / N_0}$$  

(2)

As indicated before, WT_b being a key parameter for a Gaussian filter, the degradation factor can be specified in terms of WT_b. Shown in Fig. 4, is the variation of ν as a function of WT_b.

To find the bit error probability in reference to GFSK scheme, the general form of BER (P_e) developed for FSK [3] can now be modified as follows:

$$P_e = Q(a,b) - \frac{1}{2} e^{-(a^2+b^2)/2} I_0(ab)$$  

(3)

Where:

$$a = \sqrt{\nu E_b / N_0 (1 - \sqrt{1 - |p|^2})}$$

$$b = \sqrt{\nu E_b / N_0 (1 - \sqrt{1 - |p|^2})}$$

$$|p| = \left| \frac{\sin(\Pi t\Delta f)}{\Pi t\Delta f} \right| = \left| \sin(\Pi h) \right| / \Pi h$$

h is modulation index; Q(a,b) : Marcum’s Q-function; and, I_0(a,b) : Modified Bessel function of order zero.

Fig.4 Degradation factor (ν) in Equation 2 with varying WT_b
The proof of Eqn. (3) is as follows:

As indicated by Proakis [3], with a modulation index equal to 1 and $WT_b \to \infty$, the BER ($P_e$) corresponding to the traditional FSK is given by:  $rac{1}{2} \exp \left[-\left(\frac{E_b}{N_0}\right)/2\right]$.

Now, substituting $WT_b \to \infty$ (or $\nu = 1$), $h = 1$ (or $|\rho| = 0$), $a = 0$ and $b = \sqrt{E_b / N_0}$ in Eqn (3), the result in that $Q(0,b) = e^{-b^2/2}$ and $I(0) = 1$. Therefore, Eqn. (3) reduces to

$$P_e = e^{-b^2/2} - (1/2)e^{-b^2/2} = (1/2)e^{-\frac{E_b/N_0}{2}}$$

(4)
3 Frame Error Rate in ACL Packets of Bluetooth™ Transmissions

There are seven kinds of packets as initiated in Table 1

**Table 1: ACL packets**

<table>
<thead>
<tr>
<th>Type</th>
<th>User Payload (Bytes)</th>
<th>Payload header</th>
<th>Maximum overall packet size (Bits)</th>
<th>FEC</th>
<th>CRC(16bits)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM1</td>
<td>0-17</td>
<td>1</td>
<td>(((17+1)\times8+16)\times3/2=240</td>
<td>2/3</td>
<td>Yes</td>
</tr>
<tr>
<td>DH1</td>
<td>0-27</td>
<td>1</td>
<td>((27+1)\times8+16=240</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>DM3</td>
<td>0-121</td>
<td>2</td>
<td>(((121+2)\times8+16)\times3/2=1500</td>
<td>2/3</td>
<td>Yes</td>
</tr>
<tr>
<td>DH3</td>
<td>0-183</td>
<td>2</td>
<td>((183+2)\times8+16=1496</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>DM5</td>
<td>0-224</td>
<td>2</td>
<td>(((224+2)\times8+16)\times3/2=2736</td>
<td>2/3</td>
<td>Yes</td>
</tr>
<tr>
<td>DH5</td>
<td>0-339</td>
<td>2</td>
<td>((339+2)\times8+16=1744</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>AUX1</td>
<td>0-29</td>
<td>1</td>
<td>((29+1)\times8=240</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

In reference to AUXI packet, there are no FEC and CRC; it means that no error correction and/or detection facilitated. Therefore, the whole packet may fail when any single bit error occurs in the packet. For DH1, DH3, DH5, the 16 CRC bits are included in the packet. But these CRC bits enable as error checking only through ARQ scheme, and do not offer error correction. Consequently, both AUX and DH packets do not have the capability for error correction. Hence, such packets will be discarded, whenever a single error bit occurs. The corresponding packet error probability is specified in terms of

\[
\text{FER} = 1 - (1 - P_e)^n
\]  

(5)
\[ P_e = \text{Probability of bit error rate} \]
\[ n = \text{number of bit in a AUXI or DH packet} \]

In reference to a DM packet, the information payload plus CRC bits are coded with a rate 2/3 FEC, adds 5 parity bits to every 10 bit segment codeword. This code can correct all the single errors in each codeword. Since the encoder operates with information segments of length 10, tail bits with value zero may have to be appended after the CRC bit. The total number of bits to be encoded. (that is, payload header, user data, CRC, and tail bits) must be a multiple of 10.

![Fig. 6: DM packet format](image)

The probability of error in such DM packets with each code word having the correction capability to correct the single error, is given by:

\[
P_c = 1 - \sum_{k=0}^{15} \binom{15}{k} P_e^k (1 - P_e)^{15-k}
\]

(6)

where \( P_e \) is the probability of bit error rate, and \( P_c \) is probability of codeword error rate. The corresponding probability of packet error rate is given by:

\[
\text{FER} = 1 - (1 - P_c)^m
\]

(7)

with \( m \) being the number of codeword in a packet.

4. EM RADIATION of the 3\textsuperscript{rd} harmonic of 800 MHz mobile phone versus Bluetooth\textsuperscript{TM} Transmission: Analysis

Consider the designated time-slots (of 625 \( \mu s \) each) assigned for the Bluetooth\textsuperscript{TM} transmission from the master-to-the-slave.

![Fig.: Master-to-slave Bluetooth\textsuperscript{TM} transmissions with possible EMI caused by the 3\textsuperscript{rd} harmonic of 800 MHz mobile phone](image)
slots packet, or 5 time–slots packet). Each packet is set to begin at the instant corresponding to the beginning of even time–slots in the master-to-slave link; and, whenever a packet is sent, it uses the same frequency-hopping channel over its entire duration. The possible occupancy scheme of packets across the designated (even) time–slots is illustrated in Fig. 7 (In a similar manner, the odd time–slots are occupied by the packets in the reverse transmissions from the slave-to-master.)

![Diagram](image)

**Fig. 7**: (a) Even time-slot occupancy scheme for packets in master-to-slave Bluetooth™ transmission
(b) Hopped frequency range and the corresponding channel numbers accommodating the packets in the Bluetooth™ transmission considered

The frequency-hopping channel supporting a given packet is specified by the address of the master in the piconet (ULAP: Upper & Lower Address Part) and by the current time-slot position accommodation the packet. This channel is further identified by its designated number ranging from 0 to 78 (2402 to 2481 MHz), as per the Bluetooth Core Specification V 1.0B. Each of this hopping channel has a bandwidth equal to 1 MHz and frequency hopping is set at 1600 hops/s; (hence, the time slot width is equal to 1/1600 = 625 µs as mentioned earlier)

Now, the effect of EM radiation of the 3rd harmonic of 800 MHz mobile phone on the master-to–slave Bluetooth™ communication under discussion ( Fig. 8 ) can be considered.

**Fig 8.** EM radiation from the 3rd harmonic of 800 MHz mobile phone with a spectral range that could render frequency – hopped channels of Bluetooth™ communication susceptible to EM Interference (EMI)
EM radiation from the 3rd harmonic of 800 MHz mobile phone interfering with the Bluetooth™ communication. The ensemble of computation carried out refers to simulations depicted as 6 models of mobile phone as shown in Table 2:

**Table 2** The 3rd harmonic of 800 MHz mobile phone

<table>
<thead>
<tr>
<th>Model</th>
<th>800 TX Mode (MHz)</th>
<th>3rd Harmonic (GHz)</th>
<th>Slot number</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>806.0125</td>
<td>2.4180</td>
<td>14-15</td>
</tr>
<tr>
<td>B</td>
<td>806.0625</td>
<td>2.4182</td>
<td>14-15</td>
</tr>
<tr>
<td>C</td>
<td>813.5125</td>
<td>2.4405</td>
<td>36-37</td>
</tr>
<tr>
<td>D</td>
<td>813.5625</td>
<td>2.4407</td>
<td>36-37</td>
</tr>
<tr>
<td>E</td>
<td>820.9875</td>
<td>2.4629</td>
<td>59-60</td>
</tr>
<tr>
<td>F</td>
<td>824.9875</td>
<td>2.4749</td>
<td>71-72</td>
</tr>
</tbody>
</table>

The EM radiation from the 3rd harmonic of 800 MHz mobile phone, when occurs, is sufficiently strong enough to cause interference on the Bluetooth™ transmission so that the entire packet will be dropped if the packet is in its active time and frequency range coinciding the time/ frequency encroachment of the interfering EMI from the mobile phone.

Presented in Table 3 is computed results performed with the data indicated above. The simulations were done with MATLAB™.

**Table 3 Simulated results in average frame error rate (FER)**

<table>
<thead>
<tr>
<th>Mobile Phone Model</th>
<th>Carrier frequency</th>
<th>Frame error rate (FER) Simulation</th>
<th>Average FER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>A</td>
<td>2.4180</td>
<td>0.0134</td>
<td>0.0133</td>
</tr>
<tr>
<td>B</td>
<td>2.4182</td>
<td>0.0101</td>
<td>0.0133</td>
</tr>
<tr>
<td>C</td>
<td>2.4405</td>
<td>0.0121</td>
<td>0.0068</td>
</tr>
<tr>
<td>D</td>
<td>2.4407</td>
<td>0.0159</td>
<td>0.0101</td>
</tr>
<tr>
<td>E</td>
<td>2.4629</td>
<td>0.0090</td>
<td>0.0064</td>
</tr>
<tr>
<td>F</td>
<td>2.4749</td>
<td>0.0127</td>
<td>0.0167</td>
</tr>
</tbody>
</table>
5. SIMULATION AND RESULT

At this point, there are two FERs that can be considered: One due to the packet hopping in the frequency range with a coincidence in time on the EM radiation from the 3rd harmonic of 800 MHz mobile phone and the other arising from the considering relevant to $E_b/N_0$ of GFSK. Consequently, the actual FER corresponding to Bluetooth packet interfered by the 800MHz mobile phone is

$$FER_{\text{actual}} = FER_{\text{GFSK}} \times FER_{\text{EMI-MobilePhone}}$$

(7)

All model of the mobile phone in Table 1 is chosen for this study. Fig.9- Fig.11 show the frame error rate (FER) versus $E_b/N_0$ with different modulation factors.

![Graph showing FER vs $E_b/N_0$ for different models of mobile phones.]

**Fig. 9:** Frame error rate on DM1 Bluetooth™ packet with $W_{T_b} = 0.5$ and modulation index = 0.32 interfering by the 3rd harmonic of 800 MHz mobile phone.
Fig. 10: Frame error rate on DM3 Bluetooth™ packet with $W_{T_b} = 0.5$ and modulation index = 0.32 interfering by the 3rd harmonic of 800 MHz mobile
6. CONCLUSIONS

As indicated in this research, the mode of possible interaction between EMI from the 3rd harmonic of 800 MHz mobile phone and Bluetooth™ transmissions is investigated. Assuming such EMI emerges from ISM band, namely 2.45 GHz and its spectral emission characteristics coincide with the hopped frequencies of CDMA transmissions of the Bluetooth™ communications, the resulting frame error rate (FER) is derived. Considerations of GFSK modulation adopted are duly taken into account.

Beside Bluetooth™ technology, other wireless communications systems operating in 2.4 GHz such as wireless LAN (IEEE 802.11) may also be prone to interference due to the 3rd harmonic of 800 MHz mobile phone. Also the wireless LAN, configuration (that uses either direct sequence or frequency hopping for CDMA purpose) could itself be a significant interference source for Bluetooth™ system. In short, by brute-forcing a coexistence, the Bluetooth™ and the wireless LAN may pose as interference sources to each other. Consequently, the performance of Bluetooth™ operating in the same environment with wireless LAN and/or
the 3\textsuperscript{rd} harmonic of 800 MHz mobile phone becomes a topic of concern in wireless telecommunication that warrants further studies.

\section*{REFERENCES}

