MICROWAVE OVEN SIGNAL MODELING

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ABSTRACT

The MicroWave Oven (MWO) is a commonly available appliance that does not transmit data but still radiates signals in the unlicensed 2.4 GHz Industrial, Scientific and Medical (ISM) band. The MWO thus acts as an unintentional interferer for IEEE 802.11 Wireless Fidelity (Wi-Fi) communication signals. An analytic model of the MWO signal is developed and studied in this paper. The model's efficacy is studied via simulation and experimental emulation.

Keywords—Microwave Oven; Device model; ISM Band; Interference.

I. INTRODUCTION

Wireless communications are the foundation of today's information-centric culture. The Federal Communications Commission (FCC) allocates many licensed bands but the Industrial, Scientific and Medical (ISM) [1] bands are unlicensed and, hence, very attractive for consumer applications. With the explosion of consumer electronics that operate in this frequency region, the 2.4 GHz ISM band has become known as the "wild west" of the electromagnetic spectrum. Devices that operate in the ISM bands, specifically the 2.4 GHz range, include IEEE 802.11 Wi-Fi [2] access points, wireless laptops, Bluetooth devices, cordless phones, wireless video game controllers, baby monitors, and the list continues to expand.

There are also *non-data* transmitting devices operating in these bands, specifically in the 2.4 GHz range. The most common of these unintentional interferers is the MicroWave Oven (MWO). The residential MWO has one magnetron tuned to approximately 2.45 GHz (the commercial MWO uses two magnetrons), and typically radiates across the entire Wi-Fi spectrum. This device emits electromagnetic Radio Frequency (RF) power that, when operating simultaneously and in proximity to Wi-Fi devices, can cause data loss [3] and even connection termination. For this reason, the common residential MWO is the most critical application to investigate with the goal of interference mitigation through the use of cognitive radio.

In this paper, an improved analytical model for the MWO signal is proposed, simulated, and emulated. The analytical model is the key to fully understanding the interference process. This model also is useful in wireless network simulation studies. The emulation provides a real-world test of the model, allowing for its verification.

This paper is organized as follows. Section II examines the MWO signal characteristics. The MWO signal is modeled in Section III. Simulation and emulation results of the model are given in Section IV, followed by conclusions in Section V.

II. MWO SIGNAL CHARACTERISTICS

In this section, we provide an overview of the experimentally determined signal characteristics of the MWO that lead to the development of the analytical MWO model. We explore its duty cycle, frequency-sweeping attribute, temporal envelope, and transients.

The residential MWO periodically turns ON and OFF in synchronism with the 60 Hz frequency of the AC supply line powering the MWO [4]. Hence, the MWO signal is repetitive in nature with a period of 16.67 ms. Some residential models only transmit in the negative AC line cycle, while others transmit exclusively in the positive cycle. The duty cycle of all residential MWOs is thus, at most, 50%. Energy leaking from the MWO cavity causes interference in the 2.4 GHz ISM band.

The peak-power operational frequency range of the MWO varies with the manufacturer and model. For the models tested, this range was 2.45 - 2.465 GHz. The spectrogram of MWO #1 is shown in Fig. 1. Note that the shading intensity is proportional to the MWO power, i.e., the darker the image, the higher the power. This spectrogram was obtained experimentally in the Wireless Interference Laboratory (WIL), a component of the Wireless Networking and Communications Research Center (WiNCom) at Illinois Institute of Technology (IIT) using a ComBlock receiver [5]. The ComBlock mixed the MWO signal from the 2.4 GHz range down to baseband and used a 40 MHz analog to digital converter to record the MWO signal. MATLAB® software was used to obtain the spectrogram plot. The spectrogram is very useful in exploring the MWO emissions because it experimentally reveals the characteristics of the frequency-sweeping and transient aspects of the MWO signal.

The residential MWO signal, in the ON mode, is similar to a Frequency Modulated (FM) signal with a frequency sweep, as is clearly seen in the spectrogram [6] in Fig. 1. The frequency-sweep in the MWO signal exists for less than half of the 60 Hz time period, typically 5-6 ms. During the frequency-sweeping part of the ON cycle, the radiated signal can be characterized as an FM signal with varying power levels. The latter property lends itself to an Amplitude Modulated (AM) mode. Thus, a combined AM-FM waveform will serve as a basis for the frequency-sweeping part of the signal [7]. The sinusoidal shape in Fig. 1 shows that the FM modulating signal can be well approximated by a sinusoid with a 60 Hz frequency.

The envelope of the MWO signal varies significantly during the ON cycle. This was observed from a detailed study of the spectrogram and is observed from the experimentally measured time domain envelope of the MWO #1 RF signal (Fig. 2). The amplitude of the MWO signal can be approximated by a sinusoidal waveform when the microwave oven is on.

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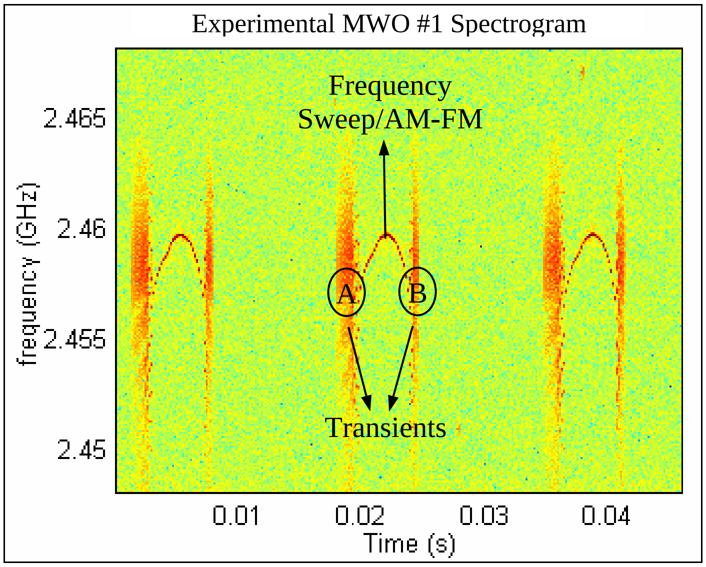

Fig. 1. Spectrogram of MWO #1 signal

Two transient signals, seen in Fig. 1, exist in each period; one at the beginning and one at the end of the ON cycle of the MWO. The transient signals are broadband with Power Spectral Densities (PSDs) [6] extending up to 60 MHz in bandwidth.

The PSD of MWO #1 is shown in Fig. 3. The lower power broadband part of the PSD is caused by the transients, while the narrow band, higher power part of the PSD is attributed to the frequency sweeping AM-FM signal. However, most of the power of the transients is concentrated at frequencies where the sweeping part of the MWO signal exists (see locations A and B in Fig. 1).

III. ANALYTICAL MODEL OF MWO SIGNAL

Based on the signal characteristics detailed in the previous section, an analytical model of the MWO signal was developed. The model is a derivative of an earlier model [8]. In this newer version, the random nature of the AM-FM signal's carrier has been modeled and the transient signal model has been greatly improved to match closely with experimental results.

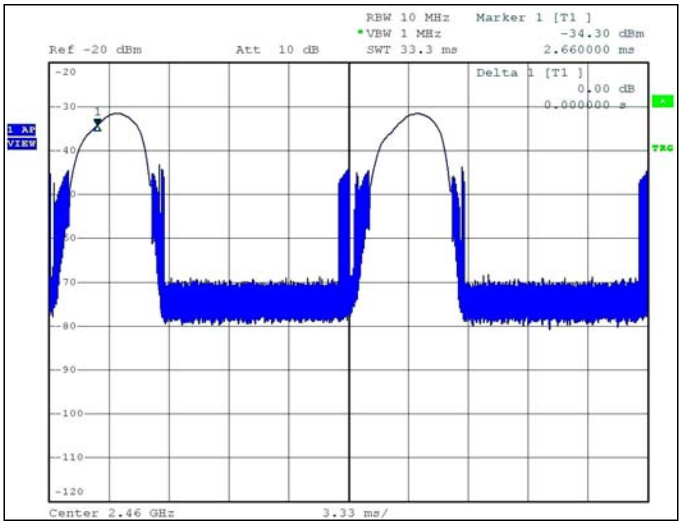

Fig. 2. The envelope of the MWO #1 signal over two 60 Hz cycles (3.33 ms/div)

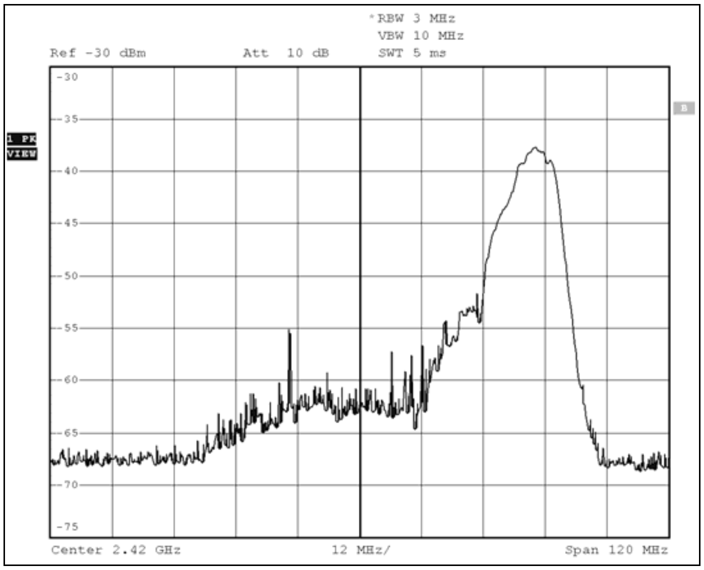

Fig. 3. Experimental PSD of MWO #1

During each period, the signal can be expressed as a sum of two transients, and an AM-FM signal to represent the frequency swept signal. The modeled AM-FM signal, $s(t)$, consists of a sinusoidally modulated FM signal with a sinusoidally shaped amplitude, $x(t)$. The AM and FM modulations are both sinusoidal in nature at the 60 Hz line frequency.

The large bandwidth of the transient signals was modeled as the sum of sinc pulses modulated at different subcarrier frequencies. Fig. 4 shows a qualitative plot of the time domain locations of these signals for each ON cycle.

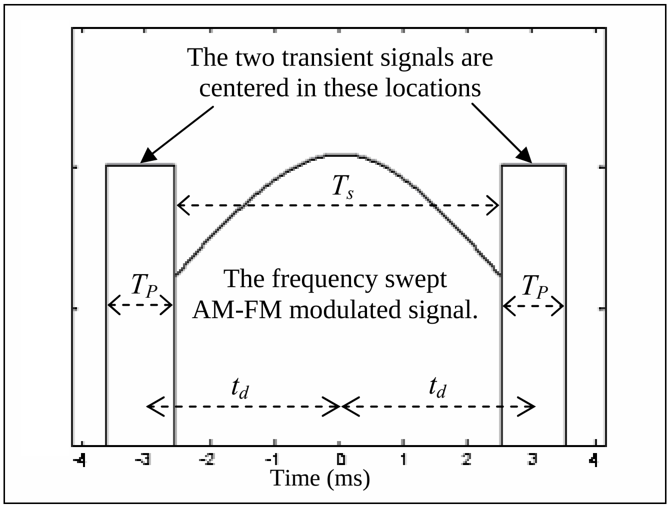

Fig. 4. Qualitative representation of MWO signal model

The complete MWO signal, $v(t)$, can be expressed as the sum of ON cycle wave-shapes, $c(t)$, that is,

$$v(t) = \sum_{n=-\infty}^{\infty} c(t - nT) \ , \qquad (1)$$

where $T = 1/f_{ac}$ and $f_{ac} = 60$ Hz.

Using the structure shown in Fig. 4 and the signal description above, the ON cycle wave-shape can be written as

$$
\begin{aligned}
c(t) &= \sum_{n=1}^{N} E\left(f_n\right) p\left(t - t_d\right)\cos\left(2\pi f_n t\right) \\
&+ \sum_{n=1}^{N} E\left(f_n\right) p\left(t + t_d\right)\cos\left(2\pi f_n t\right) \\
&+ s(t),
\end{aligned}
\qquad (2)
$$

where the transient pulse waveform is given by

$$p(t) = \mathrm{sinc}\left(b(t+\lambda_n)\right),\ \left|t\right| < 0.5T_p, \qquad (3)$$

with b a bandwidth parameter in the kilohertz range, T_P the width of the transient pulse centered at $\pm t_d$, and λ_n a random variable uniformly distributed over $\pm 0.5T_p$ to provide a time offset for each sinc pulse in the transient signal summation.

The transient signal is the sum of N sinc pulses modulated by subcarriers, f_n, uniformly spaced from f_1 to f_N. Here, f_1 and f_N are the minimum and maximum values of f_n, respectively, such that $(N-1)b = f_N - f_1$. The energy in each sinc pulse is determined by the function $E(f_n)$. Several curve fitting functions were tested for $E(f_n)$ but best results were obtained with a modified Rayleigh function [6] defined as

$$E\left(f_n\right) = E_O \frac{(f_N - f_n)}{f_h^{\,2}} e^{-\frac{(f_N-f_n)^2}{2f_h^{\,2}}}, \qquad (4)$$

where
$$f_h = f_N - f_{pk}, \qquad (5)$$

E_O is an amplitude scale factor, and f_{pk} is the subcarrier frequency with the maximum transient energy.

The AM-FM signal, with sinusoidal modulation, can be written as

$$s(t) = A\,x(t)\cos\left(2\pi F_c t + \beta\sin(2\pi f_{ac} t)\right),\ \left|t\right| < 0.5T_s; \qquad (6)$$

the amplitude variation is given by

$$x(t) = \cos(2\pi f_{ac} t), \qquad (7)$$

and the power in $s(t)$ is dictated by the amplitude, A, with the sweep time given by T_s. The peak frequency deviation is determined by the modulation index, β. The carrier frequency of the AM-FM signal is a random variable, F_c, that is uniformly distributed between frequencies f_a and f_b. During any given period, F_c is fixed, but it varies from one ON cycle to the next. The operating range of F_c, that is, $f_b - f_a$ is typically 5 MHz.

Using the model, any MWO signal can be represented by appropriately choosing a set of 13 independent parameters: f_{ac}, T_p, t_d, f_1. f_N, b, E_O, f_{pk}, β, T_s, A, f_a, and f_b. This model, when simulated and emulated, provides very good agreement to experimental measurements as detailed in the next section.

IV. MWO MODEL ACCURACY

The model described in the previous section was studied by experimentation and via simulation to examine its accuracy. An accurate model is highly useful in wireless network simulation studies. For example, simulations that study wireless network throughput and performance must account for RF interference from other radiating sources. In this case, the MWO model can be utilized as one of the wireless interferers operating in the simulated physical layer. In related work [9], certain aspects of this model were used to develop a cognitive radio circuit that mitigates interference between a MWO and an experimental Wi-Fi transmitter. The cognitive radio compares the modeled transients with received RF signals to identify when an MWO is operating.

The model in Section III was simulated using MATLAB® software. Simulations were performed in the megahertz range for computational convenience. Simulations at higher and lower frequency ranges have shown that the model is scalable to all frequencies and bandwidths without altering the general signal characteristics. Figure 5 shows a spectrogram obtained using the simulated model and Fig. 6 shows the PSD computed over 100 cycles. The parameters were chosen such that the PSD in Fig. 6 closely matched the characteristics of the MWO #1 PSD shown in Fig. 3. For computational feasibility, however, the MWO total bandwidth was limited in simulation to 1.5 MHz compared to the 60 MHz bandwidth of the experimental MWO #1 in Fig 3. To scale this simulation to a higher frequency with larger bandwidth, the transient bandwidth is increased by increasing the range between f_{pk} and f_N while keeping b the same and β, f_a and f_b are increased to increase the AM-FM signal's bandwidth.

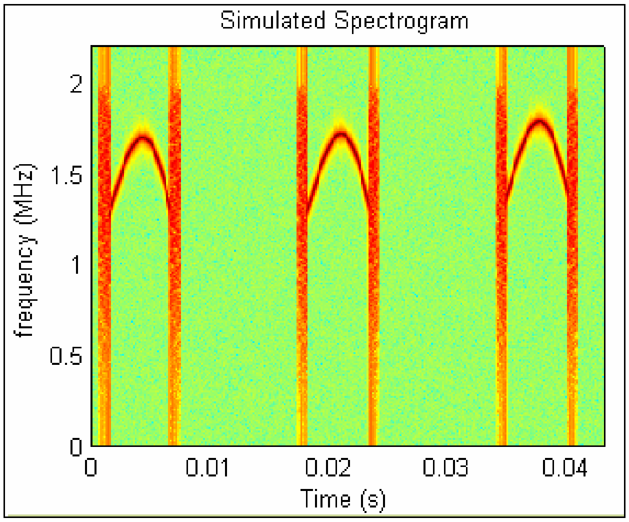

Fig. 5. Spectrogram of simulated MWO #1 signal

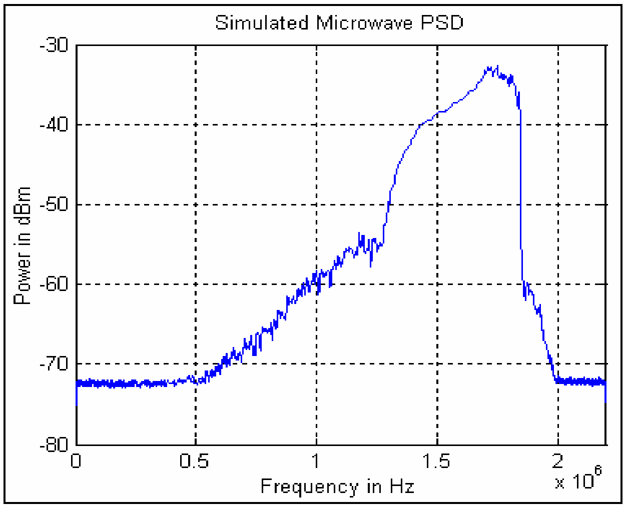

Fig. 6. Simulated PSD of MWO #1 signal

To verify the simulation studies and to further validate the model, the MWO model was emulated experimentally for a different MWO (#2). For this purpose, a ComBlock transmitter unit [5] operating in the 2.4 GHz range was used to emulate the MWO signal based on the model equations. Figure 7 shows the experimentally emulated spectrogram, and Fig. 8 is the PSD of this emulated signal obtained with a spectrum analyzer. For this emulation study, the parameters were chosen such that the PSD characteristics closely followed that of MWO #2, the PSD of which is shown in Fig. 9. Due to the experimental arbitrary signal generator's bandwidth limitations, the emulated MWO model's bandwidth was set to 1.5 MHz.

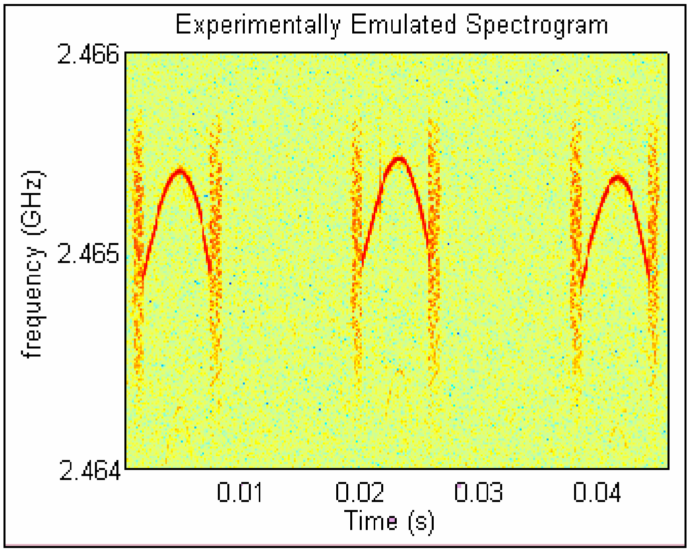

Fig. 7. Spectrogram of emulated MWO #2 signal

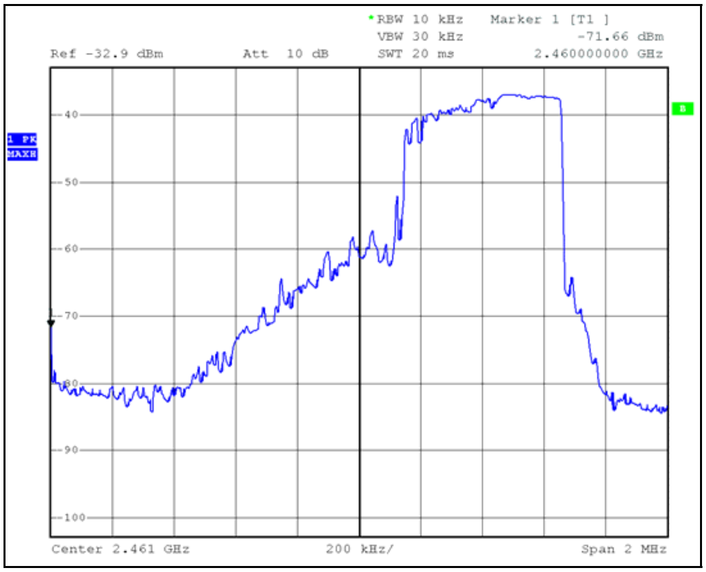

Fig. 8. PSD of emulated MWO #2 signal measured by spectrum analyzer

The simulation and emulation studies show that the model is a good approximation to the MWO signal. Furthermore, they demonstrate that the model's parameters are readily adjustable to approximately match the characteristics of different MWOs.

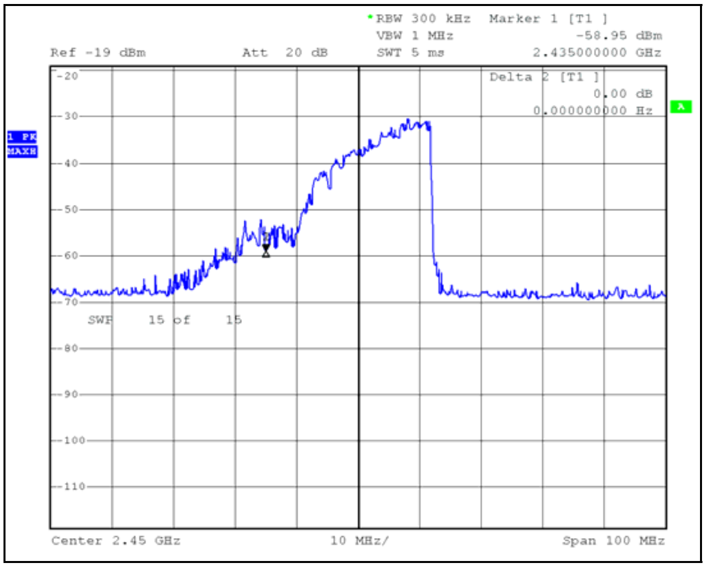

Fig. 9. Experimental PSD of actual MWO #2

V. CONCLUSION

The signal characteristics of the microwave oven were investigated and modeled in this paper. The model was studied experimentally and via simulation and closely matches the actual MWO signal. The results of this study are applicable to wireless network simulation studies and in cognitive radio devices for interference mitigation.

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