Measurement-Based Characterization of Buzz Noise in Wireless Devices

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Abstract—**When a device is communicating through wireless connections such as GSM or Wi-Fi, noise in audible range, called buzz noise, is often generated in an audio system and disturbs the audio signal quality. While the buzz noise problem has been found in wireless devices for a long time, there is little understanding of the buzz noise generation mechanism. In this paper, a buzz noise model is proposed considering demodulation and transfer function of the microphone IC front-end. The proposed model is verified through several experiments using recorded audio data in a tablet. Especially, the buzz noise caused by real Wi-Fi signals is reproduced by using the model and compared to recorded buzz noise.**

Keywords—buzz noise, microphone, Wi-Fi, wireless devices

I. INTRODUCTION

For wireless devices such as smart phones and tablets, periodic noise may be heard in the microphone recorded data when they are receiving or transmitting GSM or Wi-Fi signals. This noise is called bumblebee noise or buzz noise. The red curve in Fig. 1 shows an example of the recorded buzz noise. When the Wi-Fi is connected, audible noise will occur every 0.2 seconds. Besides that, the buzz noise has a wide-band spectrum which occupies the whole audible frequency range from 20 Hz to 20 KHz.
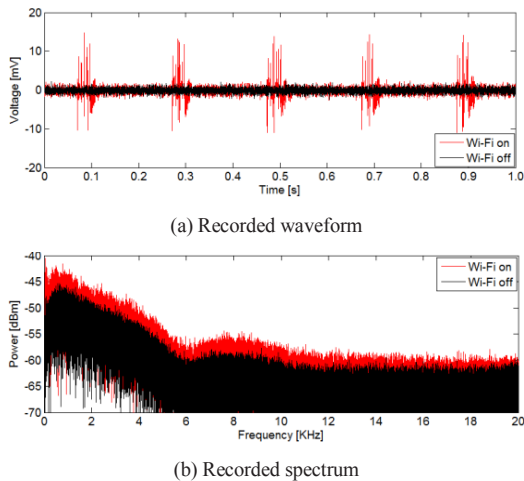

(a) Recorded waveform

(b) Recorded spectrum

Fig. 1. Comparison of the recorded data with/without buzz noise.

Unlike most of the RFI issues where the embedded antenna in the wireless device is a victim, the antenna becomes an aggressor in the buzz noise problem. Fig. 2 is an illustration of the buzz noise problem. When the device is communicating with GSM or Wi-Fi signals, the working microphone of this device will take these radio frequency (RF) signals as an input. After going through an unknown mechanism, the output of the microphone finally can be heard as the buzz noise which falls in the audio frequency (AF) range.
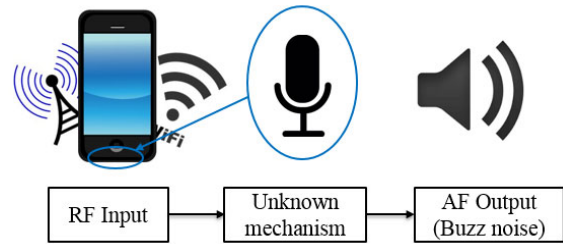

Fig. 2. Illustration of the buzz noise problem.

Buzz noise problems have been plaguing wireless devices with a microphone for decades [1-4]. The common understanding of the buzz noise is that the RF signal containing components associated with low frequency generates noise in an audible range when it couples to an audio system. However, there exists little analysis or experiment to understand the buzz noise mechanism in practical wireless devices.

In this paper, the buzz noise generation mechanism is characterized by the proposed model. First, the buzz noise caused by test signals is measured. The microphone transfer function is also characterized by a set of well-designed test signals. By comparing the spectrum of input test signals and output buzz noise, the square law demodulation method is proposed to explain the down-conversion behavior in the buzz noise problem. Then, the model combining the square law demodulation and the microphone transfer function has been checked by test signals. Furthermore, the proposed model is used to reproduce the Wi-Fi-caused buzz noise. The final comparison validates the proposed model.

II. DUT Description And Microphone Transfer Function Characterization

A. DUT Description

A tablet was used as the device under test (DUT). Fig. 3 shows the microphone and the embedded Wi-Fi antenna of this tablet. With the microphone module placed right next to the Wi-Fi antenna, it is plausible that the RF signal emitted by antenna couples to the microphone easily then causes buzz noise.
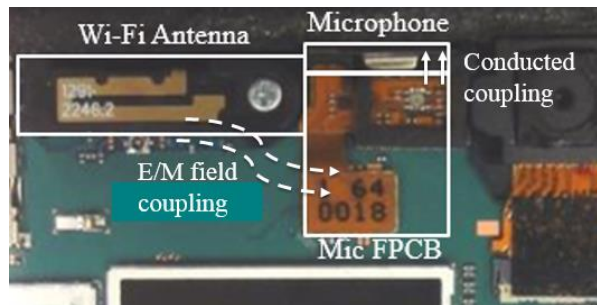

Fig. 3. Microphone IC and Wi-Fi antenna are placed right next to each other in this particular tablet.

A set of experiments were conducted to reproduce the buzz noise problem in a real-use circumstance. First, the tablet recorded noise when the Wi-Fi was off; then, the tablet recorded again when its antenna communicated with a Wi-Fi router. In both cases, just ambient noises were expected to be recorded if no interference existed. However, in the latter case, buzz noise can be clearly heard in the recorded audio file. Fig. 1 shows the recorded waveform and spectrum with and without Wi-Fi connection.

B. Measurement Set-up

Because of the complexity of Wi-Fi communication signals, it is difficult to characterize buzz noise directly in the real case with a Wi-Fi router. Fig. 4 depicts the measurement set-up for characterizing the buzz noise. A set of RF test signals was carefully generated and then initiated the embedded Wi-Fi antenna of the tablet. Similar to the real case, the test signals coupled to the microphone module and caused buzz noise.
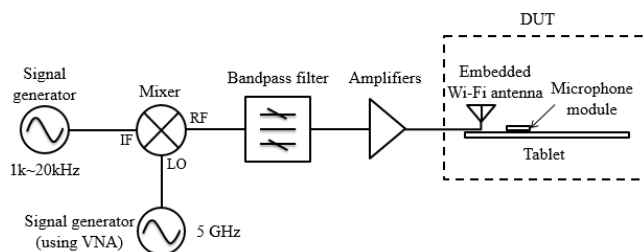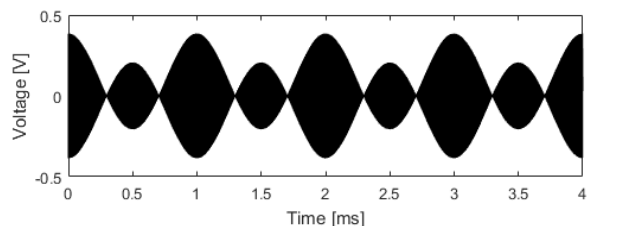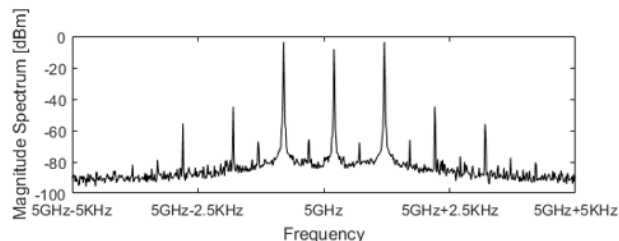

Fig. 4. Measurement set-up for characterizing the buzz noise.

In the measurement set-up, a frequency mixer was used to generate a radio frequency (RF) signal with an amplitude modulated by an audio frequency (AF) signal. The function of the bandpass filter was to remove the unwanted AF signal (low frequencies) and harmonics of the RF signal (high frequencies). Here, a vector network analyzer (VNA) was used to generate the LO signal at 5 GHz.

Compared to the real Wi-Fi signal, the RF test signal generated by the set-up in Fig. 4 was stable. The test signal was injected into the antenna as input when the microphone was working and the buzz noise was recorded by the microphone as an AF output. In this case, continuous buzz noise can be heard by playing the recorded audio files. The data of RF input and AF output is plotted in both time domain and frequency domain. For example, Fig. 5 shows the waveform and spectrum of an RF input signal. Correspondingly, Fig. 6 shows the waveform and spectrum of the recorded AF output signal.
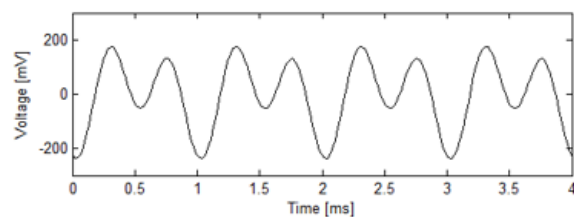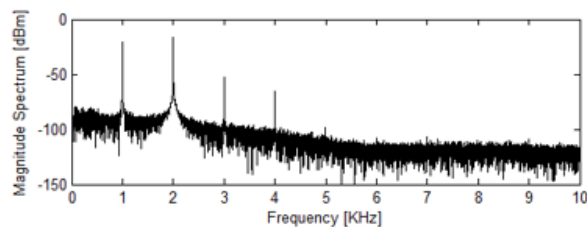

(a) Measured RF input waveform.

(b) Measured RF input spectrum.

Fig. 5. An RF input signal (the AM index is 540%).

The amplitude modulation (AM) index is adjusted by the amplitudes of the IF and LO signals. The case shown in Fig. 5 is over-modulated. Thus, the sideband frequency components have higher magnitude than the LO frequency component. Because of the nonlinear properties of the frequency mixer there are some inevitable harmonics on the two sides of the spectrum. All frequency components generated by the mixer are symmetric around the center frequency.

(a) Recorded AF output waveform.

(b) Recorded AF output spectrum.

Fig. 6. The corresponding AF output signal.

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C. Microphone Transfer Function

The sampling rate of this microphone is 44.1 KSa/sec which is enough for the audio signals. However, the signal out of the audio frequency range will be sampled as noise if there are no proper filters before the sampling. For the purpose of anti-aliasing, a low-pass filter is always used in the microphone design. It indicates that the microphone frequency response is unlikely to be constant. Also, the noise floor of all recorded data have the similar envelope as shown in Fig.1(b) which indicates the shape of noise floor should be the result of microphone transfer function.

To characterize the microphone transfer function, a set of measurements based on the set-up shown in Fig. 4 was conducted. Here, the IF input of mixer was swept so that the mixer could provide a set of RF signals which will finally caused different AF outputs from the microphone. Because the amplitude of the IF input stays the same while sweeping frequencies, the amplitude of the AF output only depends on the frequency response of the microphone. Thus, the microphone transfer function can be characterized based on the recorded data. Fig. 7 shows the result of the measured microphone transfer function.
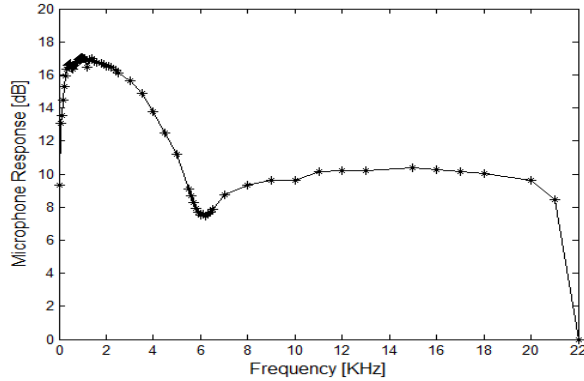

Fig. 7. Measured microphone transfer function.

More data points were measured at low frequencies and around 6 GHz is where the tendency changed. The result in Fig. 7 has been normalized by the last data point at 22.05 KHz. Finally, linear interpolation was applied to generate the complete microphone transfer function.

III. BUZZ NOISE GENERATION MECHANISM

In terms of the buzz noise generation, the mechanism when low frequency signals (AF signals) directly couple into the microphone was ruled out at first. In the measurement set-up, all possible AF signals were eliminated by a bandpass filter. However, the buzz noise problem still occurred during the measurement which means the generation of buzz noise must involve the down conversion from RF signal to AF signal. By analyzing the relationship between the recorded AF output spectrum and the measured RF input spectrum, the square law demodulation hypothesis is proposed.

According to the square law demodulation hypothesis, the RF input signal first comes to the devices with square law properties. After multiplying with the RF input signal itself, the squared signal will contain AF components besides DC and

other high frequency components. After that, the bandpass filter behavior of the microphone transfer function will largely reduce the signal strength at DC and eliminate the frequency contents in the RF range. Finally, the output is the buzz noise which can be heard. Fig. 8 illustrates how the square law demodulation and the microphone transfer function work to generate buzz noise. Note that the negative sign in the square-law demodulation is characterized from the measured buzz noise waveform.
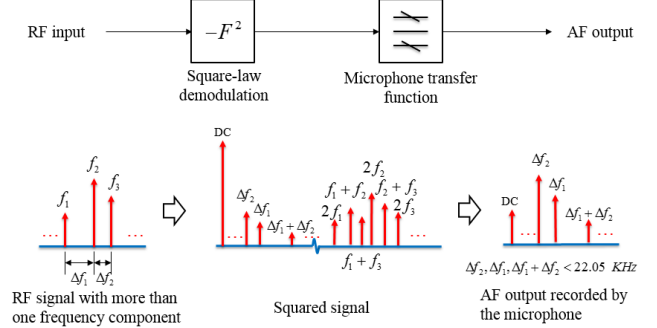

Fig. 8 The buzz noise generation mechanism based on square-law demodulation.

In Fig. 8, an example in frequency domain was used to explain the buzz noise generation mechanism. If an RF input signal contains three frequency components f_1, f_2 and f_3, its square function will generate frequency contents at DC, $f_3 - f_2, f_2 - f_1, f_3 - f_1$ as well as several frequency contents around $2f_2$. After applying the microphone transfer function on the squared signal, only the frequency components in the audio frequency range and DC component remained.

In general, let's consider a RF signal in the form of

$$s_{in}(t) = \sum_{i=1}^{N} A_i \cos(2\pi f_i t + \varphi_i), \quad (1)$$

where the signal $s_{in}(t)$ is expressed by the combination of N radio frequency components. A_i, f_i and φ_i are their amplitudes, frequencies and phases, respectively. Even though all frequencies f_i are in the RF range, the difference between the two can still be located in the AF range. Denoting the squared signal as $s_{square}(t)$, then expanding it gives:

$$
\begin{aligned}
s_{square}(t) = \left[s_{in}(t) \right]^2 &= \left(\sum_{i=1}^{N} A_i \cos(2\pi f_i t + \varphi_i) \right)^2 \\
&= \frac{1}{2} \sum_{i=1}^{N} A_i^2 \left[1 + \cos(4\pi f_i t + 2\varphi_i) \right] \\
&+ 2 \sum_{i=1}^{N} \sum_{j=1}^{i-1} A_i A_j \cos(2\pi (f_i + f_j)t + \varphi_i + \varphi_j) \\
&+ 2 \sum_{i=1}^{N} \sum_{j=1}^{i-1} A_i A_j \cos(2\pi \Delta f_{ij} t + \varphi_i - \varphi_j)
\end{aligned}
\quad (2)
$$

The last term in (2) will contain AF components if the difference between two RF components falls in the AF range. Furthermore, multiplying the squared signal with the

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microphone transfer function $MTF(f)$ in the frequency domain, the buzz noise $s_{out}(t)$ can be expressed as:

$$s_{out}(t) = F^{-1}\left\{ MTF(f) \times F\left[s_{square}(t) \right] \right\},\qquad(3)$$

where $F(\bullet)$ and $F^{-1}(\bullet)$ are the Fourier transform and the inverse Fourier transform. Equivalently, the AF output in the time domain can be written by the following equation:

$$s_{out}(t) = 2\sum_{i=1}^{N}\sum_{j=1}^{i-1}\beta(\Delta f_{ij})A_i A_j \cos(2\pi\Delta f_{ij}t + \varphi_i - \varphi_j),$$
$$(4)$$

where $\beta(\Delta f_{ij})$ is the equivalent microphone transfer function coefficient in the time domain. The $\Delta f_{ij} = f_i - f_j < 22.05 KHz$ in (4). For the same input signal shown in Fig. 5, a simulated output is obtained by using the proposed model. Fig. 9 shows the simulated output waveform and spectrum.

(a) Simulated AF output waveform.
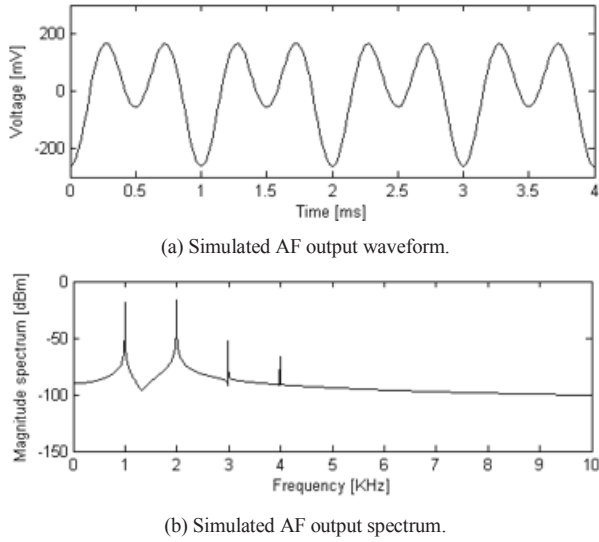

(b) Simulated AF output spectrum.

Fig. 9. Simulated result of the square function hypothesis.

Comparing the simulation results shown in Fig. 9 with the recorded data shown in Fig. 6, the proposed model characterized the buzz noise generation mechanism very well. Especially in the frequency domain, the proposed model generated the same frequency contents and similar magnitudes as those recorded by the microphone. The small difference in the time domain could be caused by the phase issue in simulation. That is, the different frequency contents may have different phases in the real measurement which will cause the asymmetrical positive peaks as shown in Fig. 6 (a). However, the phase difference of the input signal has been ignored in the simulation. As a result, the simulated output waveform has symmetric peaks as shown in Fig. 9 (a). If applying the phase differences in the simulation, similar waveforms with asymmetric peaks will be observed.

IV. REPRODUCE THE WI-FI-CAUSED BUZZ NOISE

Based on the proposed buzz noise model, the Wi-Fi-caused buzz noise also can be reproduced numerically from the Wi-Fi signal. Since the 5 GHz Wi-Fi signal requires at least a 10 GSa/sec sampling rate, it is impossible to record enough data

by a common oscilloscope. In practice, the original Wi-Fi is down-converted by a mixer. Then, the post-processing code which includes the square-law demodulation, the microphone transfer function, and the resampling function is applied on the recorded down-converted Wi-Fi signal directly. Finally, the proposed model is supported by the agreement of the post-processing result and the real Wi-Fi caused buzz noise.

In the real case, the center frequency of Wi-Fi channel #40 is 5.2 GHz and the bandwidth is 20 MHz. In the set-up shown in Fig. 10, the original Wi-Fi signal was measured by a resonant H-field probe. A 5.189 GHz signal was initiated on the LO port of the mixer. Thus, the original Wi-Fi band was down-converted to the band whose center frequency is 11 MHz and bandwidth is still 20 MHz. The other output of the mixer can be eliminated by a low-pass filter. Amplifiers were used to enhance the signal strength. The down-converted Wi-Fi signal was measured by the oscilloscope. The post processing is then applied on the data recorded by the oscilloscope.
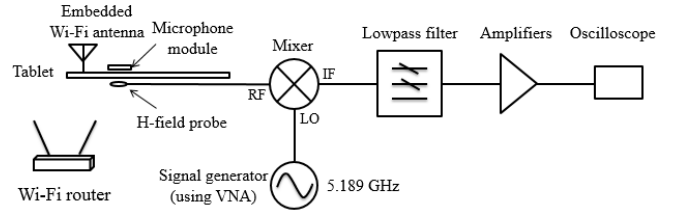

Fig. 10 Measurement set-up for recording the down-converted Wi-Fi signal and the Wi-Fi caused buzz noise.

The sampling rate of oscilloscope was set as 100 MSa/sec. Thus, the Nyquist frequency is 50 MHz. As shown in Fig. 11, the down-converted Wi-Fi signal has already moved the Wi-Fi channel #40 from 5.2 GHz to 11 MHz. At the same time, the bandwidth and the other properties do not change.

(a) Waveform recorded by oscilloscope.

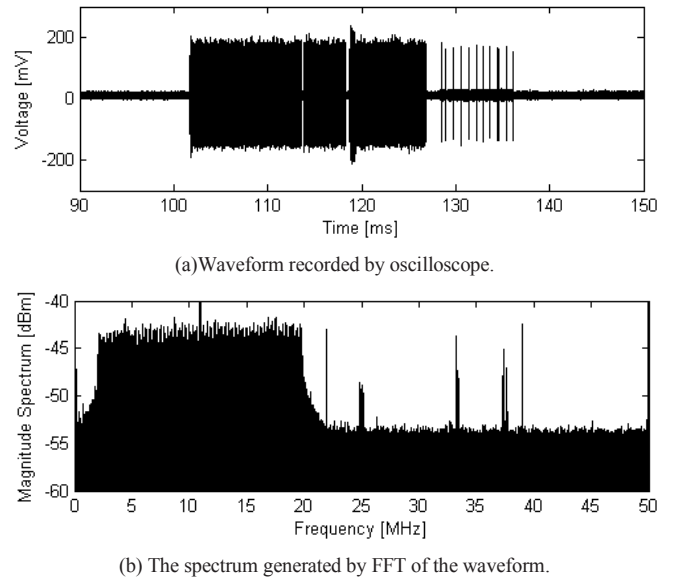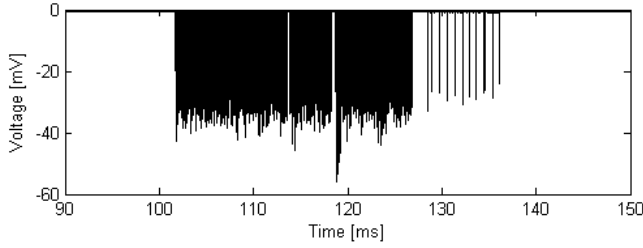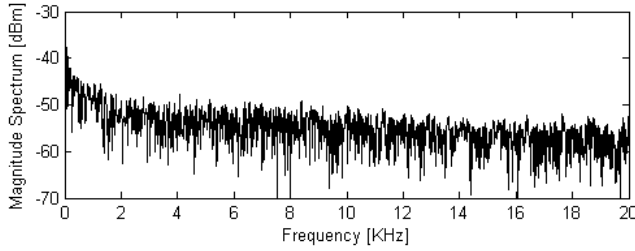
(b) The spectrum generated by FFT of the waveform.

Fig. 11 The down-converted Wi-Fi signal.

After applying the square-law demodulation in the time domain, all values became non-positive. Fig. 12 (a) shows the waveform of the negative squared signal. Fig. 12 (b) shows the

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spectrum in the audio frequency range that are generated by the square-law demodulation.
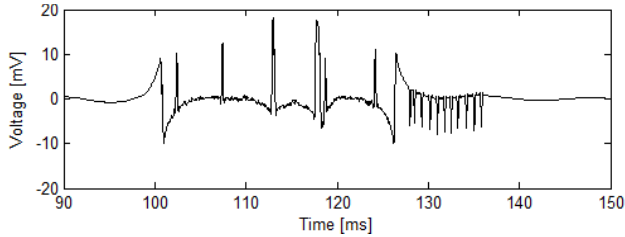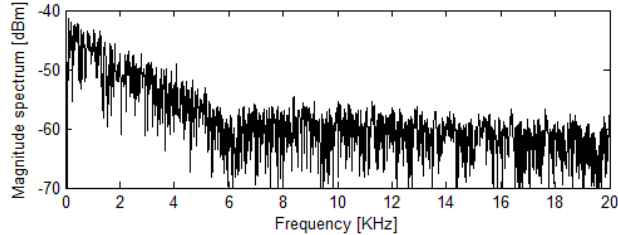

(a) Waveform of the squared data

(b) The spectrum generated by FFT of the waveform.

Fig. 12 Data after the square function.

Taking the microphone transfer function shown in Fig. 7 into account, the reproduced data based on the proposed model is exhibited in Fig. 13 (a) and Fig. 13 (b).
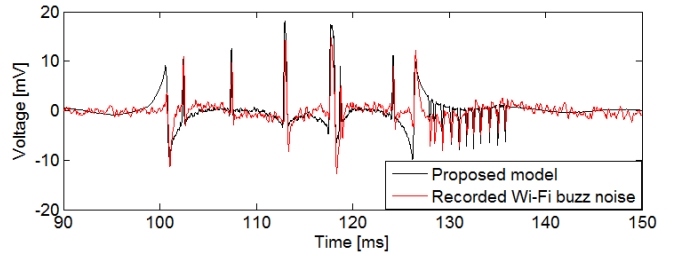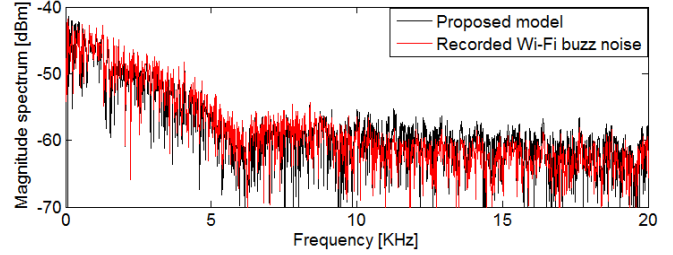

(a) Waveform generated by IFFT of the spectrum.

(b) The spectrum after multiplying with the microphone response.

Fig. 13 The reproduced data based on the proposed model.

The comparison between the reproduced buzz noise and the recorded Wi-Fi-caused buzz noise is shown in Fig. 14 where the black curve is the reproduced buzz noise and the red curve is the recorded buzz noise. The result based on the proposed model exhibits good agreement with the real case buzz noise.

(a) Agreement on the waveform.

(b) Agreement on the spectrum.

Fig. 14 The comparison of reproduced buzz noise and the recorded buzz noise.

V.   CONCLUSION

The buzz noise problem involves the frequency down conversion from the RF to the AF. The buzz noise generation mechanism can be summarized as the result of the square law demodulation followed by the microphone transfer function. The proposed buzz noise model is first proved by test signals. In terms of the real Wi-Fi signals, the post-processing code based on the proposed model is then applied on the down-converted Wi-Fi signal. The result after post-processing agrees with the real case Wi-Fi-caused buzz noise in both time and frequency domain. These validation results support that the understanding of the buzz noise mechanism is correct.

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