Memorias del 2023 Congreso Nacional de Control Automático
25-27 de Octubre, 2023. Acapulco, Guerrero, México.

Performance Analysis of Bluetooth Audio Devices as Wireless Data Acquisition Systems ⋆

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Abstract: Data acquisition is an ubiquitous process to gather information about real-world phenomena to be processed in the digital domain. Currently, portable and wireless devices have become attractive devices for measuring several processes. However, when a high-sampling-rate is required, data acquisition systems (DAS) are still expensive and targeted at a very small niche market. Moreover, low-cost DAS are affordable but they are resource-limited mainly resulting in a low-sample-rate. Interestingly, audio-based systems are versatile, their sampling frequency ranges from 1 kHz to 192 kHz, and support input voltages from ±1.0 V at 16-bit resolution. Furthermore, Bluetooth audio devices (BTAD) are currently, popular in personal devices, which stream bunches of data using electromagnetic waves in the radio-frequency band. Nonetheless, audio-focused devices are optimized to respond to signals within the audible spectral range (20 Hz to 20 kHz), which represents a limitation to work as general-purpose DAS. In this work, we assess the advantages and limitations of low-cost BTAD to work as wireless DAS by increasing its performance and reliability. For this purpose, we introduce a robust data processing technique based on spectral analysis. Finally, the functionality of different BTADs is evaluated over a frequency range out of their native limits, and a compensation method for the frequency bias is proposed.

Keywords: Data acquisition, virtual instruments, measurement and instrumentation, data-based control, input and excitation design

1. INTRODUCTION

As the power of Bluetooth audio devices (BTAD) has increased, the idea of cheap prototyping of wireless data acquisition systems (DAS), without the need to use dedicated micro-controllers, can be faced.

The usage and application of BTAD can find applications in many fields, from industrial to biomedical, including wearable systems for human activity tracking, sensors and control systems, to mention only a few. The current trend of reducing the cost of DAS is paving the road to the use of BTADs as affordable devices, however, it remains a technological challenge.

In general, a BTAD uses an internal analog-to-digital converter (ADC) that converts a continuous-time input signal to digital data. When a continuous-time signal $x(t)$ enters an ADC, the signal is represented by a discrete-time signal $x[n]$ by mapping the analog signal samples to signed integers in time intervals called sampling period, T, (Oppenheim et al., 1999). This leads to the sequence

$$x[n] = x(nT), \text{ for } n = 1, 2, \ldots, N \tag{1}$$

In practice, $x[n]$ is a scaled and finite precision version of $x(t)$. Moreover, it is worth remembering that the sampling frequency, $f_s = 1/T$, must be equal to or greater than twice the highest frequency of the signal to avoid aliasing effects. Indeed, this sampling theorem is a limitation for BTAD and could be improved using advanced signal processing techniques.

In this paper, we aim to evaluate the functionality of different BTADs and their response to a variety of commonly used waveforms. Due to the sound-focused devices are optimized to respond to signals within the audible spectral range, we introduce digital signal processing (DSP) techniques to overcome inherent limitations. Finally, we show experimental results on single sine and multisine test signals, to provide assess the performance of the proposal.

⋆ This works was supported by the grant UNAM-PAPIME PE100523.

2. BACKGROUND

2.1 Audio devices

The use of audio devices as DAS has become popular in recent years. Previous works demonstrate the effectiveness of personal computer (PC) sound cards and universal serial bus (USB) external sound interfaces (Mark Wickert, 2018) for acquiring analog signals. Interestingly, a generic sound card is a multi-channel analog to digital signal, and vice versa, conversion system. Generally speaking, sound-based devices work for input signals with an amplitude of ±1 V, in the frequency band of 20 Hz to 20 kHz. The sample rate is usually at least 48 kHz and often 96 kHz, with a 16-bit digitizing resolution (Xian-ling, 2010).

Regarding its application, sound cards have proven to be effective in the measurement of mechanical vibrations (Barros et al., 2015), acquisition of electro-cardio signals (Quan et al., 2011) and optoelectronic signal analysis (Neitzert and Rainone, 2007). Furthermore, virtual oscilloscopes and waveform generators have been developed around sound cards and dedicated software such as LabVIEW (Xian-ling, 2010; Quan et al., 2011; Yi, 2010), Matlab (Gunawan and Khalifa, 2010) and Python (Mark Wickert, 2018). Digital oscilloscopes built from sound cards accurately display the external signals acquired by the sound card in real-time.

One of the main problems affecting signal measurements with sound cards is the limitation in the frequency range of operation, which in turn, limits its application. For instance, the absolute error during the acquisition of signals in audio cards increases at low frequencies, being greater in the range of 1 to 10 Hz, and has its minimum at frequencies close to 1 kHz (Neitzert and Rainone, 2007). To overcome this situation, in Quan et al. (2011), the problem was addressed from the standard amplitude modulation (AM), however, this in turn limits the bandwidth of the signal that can be processed.

Even when audio devices often use sampling rates of 44.1 kHz, modern ADC in audio devices have a tunable f_s between 1 kHz to 192 kHz (Mark Wickert, 2018). However, acceptable voice reproduction can be accomplished with frequencies from 20 Hz to 4 kHz (Mateski and Anastasovski, 2012; Maher, 2018), so most of the devices focused on voice have bandpass filters at this frequency band.

2.2 Bluetooth technology

Bluetooth is a short-range wireless technology that is used for exchanging data between devices using ultra-high-frequency radio waves. BTAD communicates using electromagnetic waves around 123 mm wavelength (Shorey and Miller, 2000). A Bluetooth profile is a set of capabilities provided to support a particular task. Bluetooth audio has developed over time to support additional use cases as they have evolved. Although audio is bi-directional, each Bluetooth audio profile has two sides that are not interchangeable since one needs to be in control.

According to Lindqvist (2007), the advanced audio distribution profile (A2DP) is the Bluetooth standard profile for the transfer of high-quality stereo audio signals. A2DP defines two roles: Sink and Source. Where the TX acts as a source and the RX is a sink. Some A2DP devices can support both roles, not simultaneously though. Many A2DP-supporting devices also implement a hands-free profile (HFP) for use with bi-directional audio for phone calls and legacy devices. Usually, the source and the sink can be separated by up to 10 meters.

Generic and relatively inexpensive Bluetooth-based wireless data acquisition and control systems are generally based on universal asynchronous receiver-transmitter (UART) (Hu et al., 2012) systems and are based on Bluetooth Modules such as the ROK101008 (Xuange and Ying, 2010; Hongjun et al., 2009), the HC-05 and HC-06 (Misiruk et al., 2016; Wang, 2014), or the ESP32 (Sophia et al., 2021). Although this allows the interaction with other systems to send data, it also limits the ability of devices to sample high-frequency signals, because the sampling frequency is low, just a few kHz (Tsai et al., 2021). In addition, the resolution is usually below 12 bits and they only have one channel. Therefore, the use of BTAD devices is a viable alternative for the acquisition of analog signals, remains a challenging task.

3. MATERIALS AND METHODS

Fig. 1 shows the block diagram of the proposed methodology. First, a signal is generated from a computer, and it is transmitted by wire to the BTAD. Internally the device's ADC system transforms the signal into a set of binary data which is sent via Bluetooth back to the computer. Then, the input data is decoded to finally be analyzed. The acquired signals will be evaluated using spectral and statistical analysis in order to obtain a function that allows recovering the frequency and amplitude of the generated signal.

3.1 Test signals

The use of single sine and multisine signals is proposed to evaluate the performance of BTAD. According to Schoukens et al. (1988), a multisine is the sum of a given number of harmonically related sines with adjustable amplitudes and phases. The phase of the frequency components is optimized to reduce the crest factor. The multisine signal shows a uniform distribution throughout its frequency response, making it ideal for DAS test and design (Li et al., 2022). It is possible to define multisine signals from their features such as the starting frequency (f_1), the ending frequency (f_2), their amplitude (A) and the number of samples (N). Similarly, we have defined the sine signals used from these features. Table 1 summarizes the test signals used in this work.

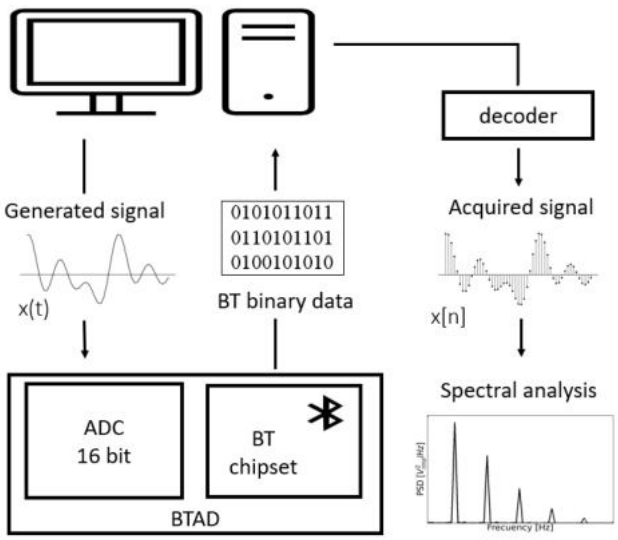

Fig. 1. Block diagram of the proposed methodology to evaluate the BTAD performance.

Table 1. Signals features for testing BTAD

	Type	f_1 **(Hz)**	f_2 **(Hz)**	A **(mV)**	**N**
0	multisine	1	8 k	500 (max)	320 k
1	sine	2	-	500	80 k
2	sine	5	-	500	32 k
3	sine	10	-	500	16 k
4	sine	20	-	500	8 k
5	sine	50	-	500	3.2 k
6	sine	100	-	500	1.6 k
7	sine	200	-	500	800
8	sine	500	-	500	320
9	sine	1 k	-	500	160
10	sine	2 k	-	500	80

The signals are generated and then acquired by the BTAD to further perform a spectral study using the fast Fourier transform (FFT). If a certain frequency persists over time, the magnitude of the FFT at that frequency increases proportionally over time. In this work, we decide to scale this result by dividing by the duration (t) of the generated signal, in the analysis of single sine signals, where t is given by

$$t = N \times f_s. \tag{2}$$

3.2 Bluetooth audio devices

Since computers typically use the A2DP protocol as a source using devices with the same configuration is infeasible. However, with a sink A2DP-supporting device that also implements the HFP, bi-directional sending of data is possible. Fig. 2 shows the two BTAD used in this work: BK8000L (Fig. 2a) and C28 (Fib. 2b).

The BK8000L is an integrated and commercial BTAD single-chip (Shenzhenshi Xinzhongxin Technology, 2018). The line-in input pins connect to the internal ADC to

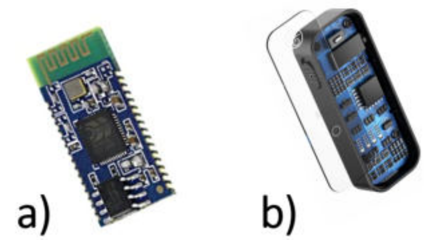

Fig. 2. The bluetooth audio devices evaluated in this work. (**a**) The BK8000L integrated Bluetooth audio chip. (**d**) The C-28 audio adapter.

convert the input signal into digital data. On the other hand, the C28 is an audio adapter that can be used as a RX or TX BTAD. In its configuration as a sink, it is possible to use its built-in microphone. Being a built-in device, it was necessary to disassemble its internal microphone to use these pins as input for the test signal.

Both devices accept an input voltage in the range of ± 1.0 V with a 16-bit resolution. Also, the sampling frequency f_s can be tuned from 1 kHz to 192 kHz, and for this work, they were configured with a f_s of 32 kHz for multisine signals and 16 kHz for sine signals.

4. RESULTS AND DISCUSSION

4.1 Multisine analysis

Fig. 3 shows the time-domain multisine signal used to evaluate the performance of the BTAD (see Table 1). The generated signal is shown in Fig. 3a), the acquired signal using the BK8000L is shown in Fig. 3b), and the acquired signal using the C28 is shown in Fig. 3c). In both cases of the acquired signals, there is a decay in the quality and amplitude of the signals for the different frequencies. However, this is more noticeable in the BK8000L signal. In fact, this situation could be attributed to the inherent band-pass filter within the audio-based devices, which is attenuating the low-frequency content of the signal.

A clearer representation of the signals can be seen in Fig. 4, where one can see the spectral analysis of the three signals: the generated one (red), the BK8000L filtered signal (blue), and the C28 signal (green). The spectrum of the generated signal shows a uniform distribution along with the whole frequency range, unlike the acquired signals. The BK8000L signal seems to have a peak close to 1 kHz and decay for lower frequencies reaching less than -30 dB for frequencies below 100 Hz. It is worth highlighting the presence of an amplitude drop close to 4 kHz. Shortly, before reaching this frequency, the response of the acquired signal dramatically drops down to -60 dB. The C28 performs in a similar way. However, the frequency band for this device is 8 kHz and maintains a

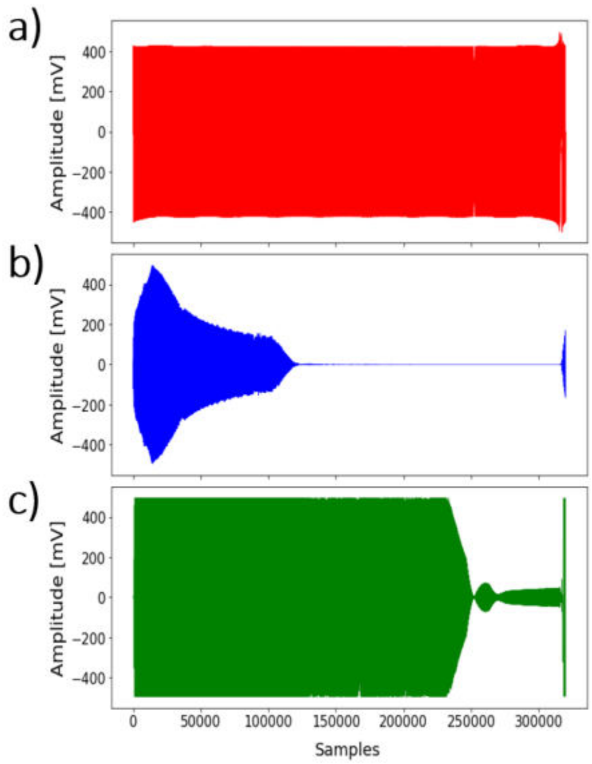

Fig. 3. The multisine signal used to evaluate the performance of the devices. (**a**) The generated signal is shown in red. (**b**) The acquired signal using the BK8000L is shown in blue. (**c**) The acquired signal using the C28 is shown in green.

uniform distribution for frequencies greater than 100 Hz. At a glance, it can be deduced that C28 has a broader frequency range of operation, thus resulting in a higher signal acquisition fidelity.

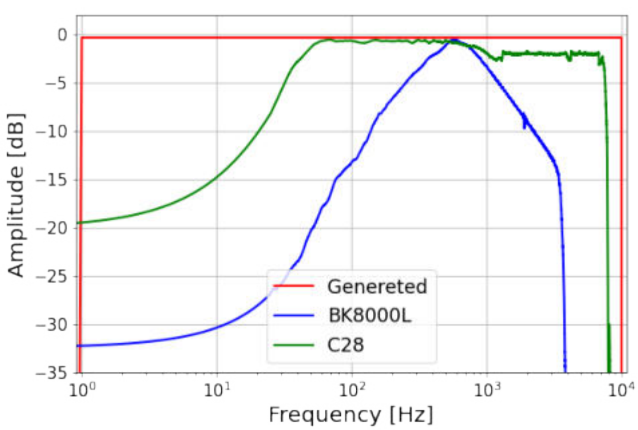

Fig. 4. Spectral analysis in dB of the multisine signal using the BK8000L. The generated signal is shown in blue and the acquired one is shown in red.

4.2 Single sine analysis

Using the information discovered, we made tests using ten different single-tone sine signals with frequencies distributed between 2 Hz and 2 kHz. Once the signals were recorded, they were processed by spectral filtering. It works from a bandpass filter on the FFT of the original signal, which recovers only the original frequency and removes the undesired harmonics, thus allowing to obtain of the original sine wave. Fig. 5 shows an example of the power spectral density (PSD) of four single sine signals: a) 2 Hz, b) 20 Hz, c) 200 Hz and d) 2 kHz using the BK8000L device. The PSD of the acquired signals are shown in blue and the PSD of the spectral filtered signals are shown overlaid in red. The harmonic distortion present in the blue signals is observed in the form of a series of peaks at odd frequencies of the fundamental frequency for each case. Comparing the four subplots in Fig. 5, it can be seen that the maximum amplitude of the PSD is higher at 200 Hz and decreases for frequencies around it. Furthermore, harmonic distortion increases as the sampled frequency decreases and decreases until it disappears at frequencies of thousands of Hz. This situation confirms that the ADC of the BTAD distorts the acquired signal, however, by spectral filtering it is possible to remove non-desired artifacts to recover the original signal.

Subsequently, the inverse fast Fourier transform (IFFT) was computed for the filtered signal, and its amplitude was then compared to the amplitude of the originally generated signal to obtain an amplitude ratio. Fig. 6 shows the statistical analysis of the ratios obtained for the evaluated frequency. Interestingly, at low frequencies, the uncertainty in the computation is larger than at high frequencies. Ultimately, the mean value of the ratios was computed for each group of frequencies to create an interpolation method for predicting the amplitude ratio.

4.3 Testing the method

To test the method, we acquired new single sine signals at frequencies that had not been considered during the previous analysis. Then, we filtered the signal to remove harmonics and multiplied the spectral signal by the corresponding value in the interpolation function and further multiplied by T (2). Fig. 7 shows the results for three sine waves with $A = 500$ mV and frequencies of a) 8 Hz, b) 150 Hz and c) 1.4 kHz. The acquired signals are shown in blue and the enhanced signals with our proposal are shown in red. Therein, it is worth noticing how our method can recover the signal morphology by eliminating harmonic distortions. On the other hand, the amplitude reaches almost 90% of accuracy in all cases, provided the interpolation method uses the ratios computed in the previous step.

5. CONCLUSIONS AND FUTURE WORK

In this paper, we propose a methodology for the use of BTAD as an attractive wireless data acquisition device.

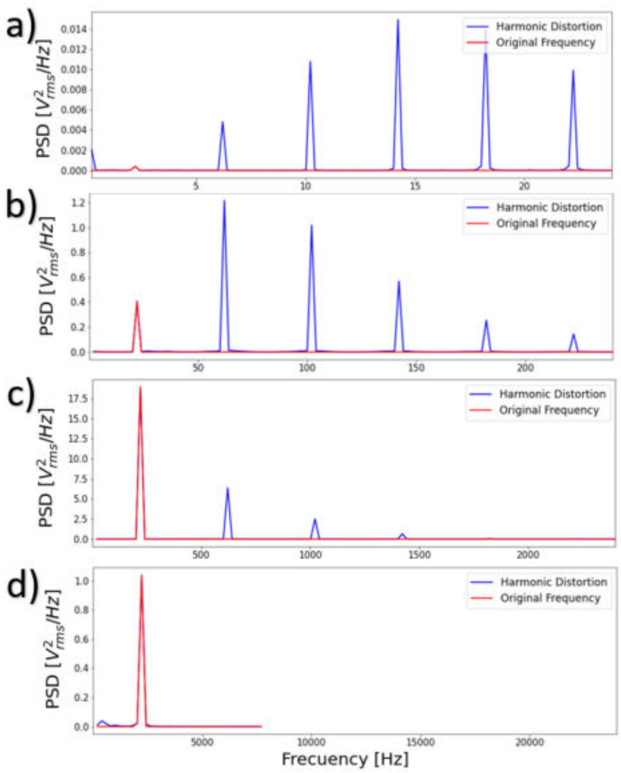

Fig. 5. Power Spectral Density (PSD) of four different single sine signals. (**a**) 2 Hz. (**b**) 20 Hz. (**c**) 200 Hz. (**d**) 2 kHz. In each subplot, the acquired signal with harmonic distortion is shown in blue and the spectrally filtered signal with just the original frequency is shown in red.

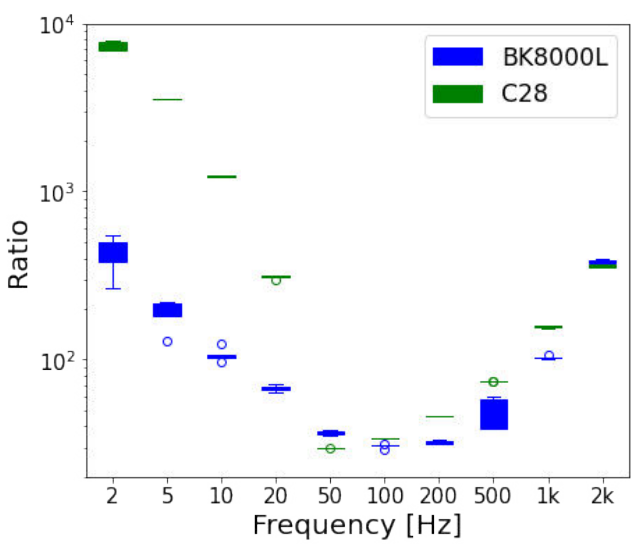

Fig. 6. Statistical analysis of each frequency group. Shows a similar response to the results obtained in the spectral analysis of the multisine signal.

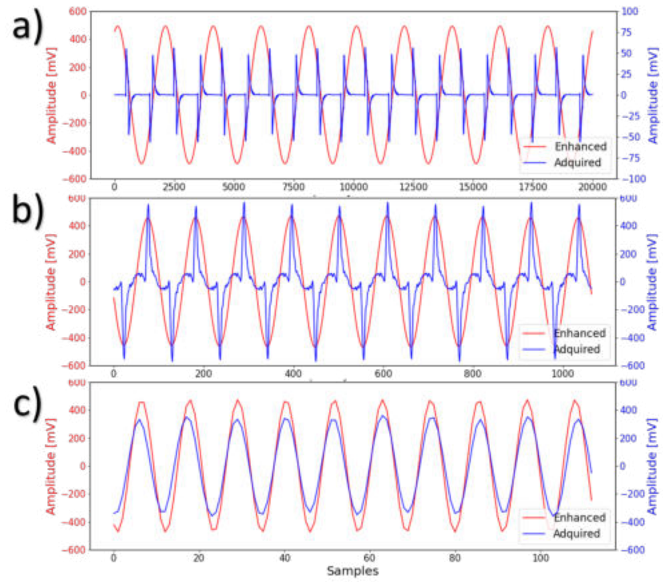

Fig. 7. The recovery of morphology and amplitude of three single sine signals using the proposed method. The acquired signals are shown in blue and the enhanced signals are shown in red. (**a**) 8 Hz. (**b**) 150 Hz. (**c**) 1.4 kHz.

The methodology was tested with two BTADs with different characteristics. We show the performance of spectral filtering to recover the waveform despite the presence of harmonics created by the devices. In addition, we were able to recover the amplitude from a multiplication process by an interpolation factor with promising results. Preliminary results indicated that BTAD together with DSP techniques leads to a powerful tool for wireless data acquisition. The advantages of these devices rely on their low cost, size and versatility, towards affordable DAS for portable applications. However, inherent limitations, such as the maximum sampling frequency, remain challenging. Therefore, more studies should be addressed to improve the BTAD performance based on sparse sampling, for instance. We showed how the methodology could serve as a proof of concept to design cost-effective DAS, showing enough sensitivity and accuracy for the recovery of sine signals.

In further work, we aim to apply the proposed methodology in acquiring biomedical signals to develop wearable wireless devices, such as bioimpedance and seismocardiography. Also, it is devised to design robust DAS for a wide variety of instrumentation processes for scientific purposes, as well as in teaching environments.

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