Measuring Audio Latencies

Using the Ellisys Audio Grabber

Overview

In this Expert Note, we will discuss latencies typically present in Bluetooth audio systems and how to use the Ellisys **Audio Grabber** (Figure 1) in conjunction with integrated audio-related features available in the Ellisys Bluetooth analyzer software and hardware to characterize these latencies.

The Audio Grabber is a small accessory for use with all Ellisys Bluetooth analyzer models. It allows for precise, time-synchronized capture and measurement of audio latencies involving analog audio signals and I2S (Inter-IC Sound) digital audio inputs, all synchronized to any other traffic streams captured by the analyzer, such as Bluetooth wireless audio, Host Controller Interface (HCI) traffic, Wi-Fi, I2C, UART, and others.

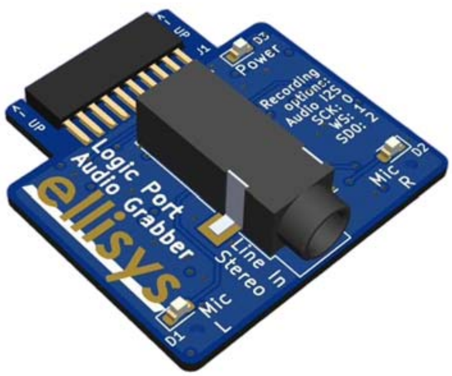

Figure 1 - Audio Grabber Accessory

The Audio Grabber connects to the analyzer's Logic port, either directly or through an adapter (to get access to additional logic lines by connecting flying leads). It can fit Bluetooth Tracker and Bluetooth Vanguard models directly but must be adapted for use with Bluetooth Explorer (with the provided adapter).

The Audio Grabber supports two mono analog inputs / one stereo input (L and R), either Line IN (3.5 mm TRS), Microphones, or a mix of line and microphones. It converts the analog audio channels to I2S digital audio for time-synchronized display in the analyzer's Audio and Timing views. This two-channel audio input (now in digital form) is hardwired onto Logic inputs 0, 1, and 2 (signals SCK, WS, and SD0, respectively). These inputs must be configured in the Recording Options dialog, Wired tab of the analyzer application. For convenience, these inputs are printed on the Audio Grabber PCB.

The two MIC inputs (L and R) are typically for use when capturing audio from ear buds, which can be placed near the MICs.

Three LEDs are also present, one each for activity at the L and R MICs and another to indicate the Audio Grabber is powered from the analyzer Logic connector to which it is attached (either directly or through the adapter).

Using the Adapter and the Flying Leads Probe

The adapter (Figure 2) is used to facilitate concurrent and time-synchronized capture of other signals, when needed, such as I2S digital audio, UART, commonly used audio control protocols like I2C and SPI, logic signals, and other traffic types, by use of a Flying Leads probe (Figure 4), supplied standard with all Ellisys analyzers. See the section titled Flying Leads Probe – Bluetooth Tracker and Vanguard for more information on connecting the Flying Leads probe.

Note: The adapter *must* be used with Bluetooth Explorer analyzers, as the Logic connector on Bluetooth Explorer is of a larger size than is used on the Audio Grabber; it is optional for Bluetooth Tracker and Vanguard.

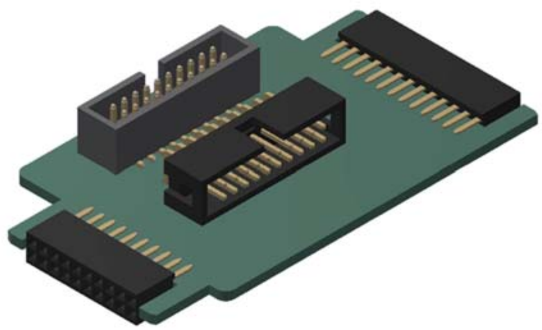

Figure 2 - Adapter for Audio Grabber

Looking at Figure 2 (above), the connector at left will attach to the Logic port on Bluetooth Tracker or Vanguard. The connector at right attaches to Bluetooth Explorer's Logic port. There are two center-mounted connectors – the connector at back allows for insertion of the flying leads probe, and the other accommodates the connection of the Audio Grabber (see Figure 3, below).

Figure 3 - Audio Grabber Inserted into Adapter

The Flying Leads probe is shown in Figure 4 (below). The probe is purely passive and uses color-coded, socket-tipped wires which can be assigned in the analyzer's Recording Options dialog, Wired tab. In addition to I2S, the probe facilitates concurrent, time-synchronized capture of UART (HCI and Generic), SPI (HCI and Generic) logic signals (up to 16), I2C, SWD, and UCI (a UWB signal command interface). Refer to the sections Flying Leads Probe – Bluetooth Tracker and Vanguard and Flying Leads Probe – Bluetooth Explorer for pinouts.

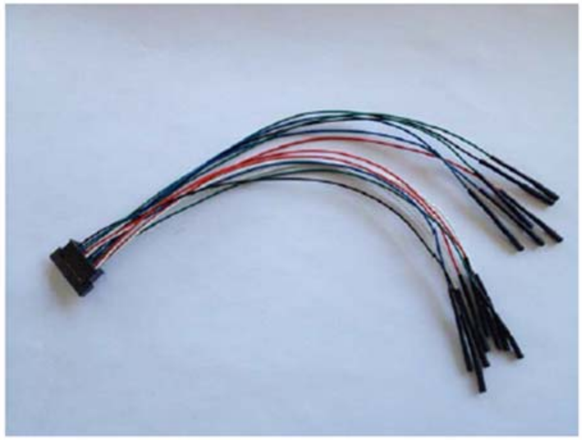

Figure 4 - Flying Leads Probe

Audio Latencies

Audio systems must ideally deliver audio streams to users with near-perfect synchronizations, as even small variances in the rendering of audio streams, for example, L and R stereo streams, can result in poor user experiences.

Audio latency can be defined as the time it takes for an audio signal to traverse a system from input to output. Such systems might be large, such as a theater or outdoor concert venue, where the speed of sound can play a role, or small, such as an electronic device, component, or module, where latencies are present from a variety of processing and transport requirements.

For our purposes here, we are more concerned with smaller-scale implementations, like component- or modular-level signal processing or implementations involving two communicating devices, where digital and analog representations of audio will be subject to various delays (see Figure 5, below). Delays realized through digital-to-analog converters (DACs) and analog-to-digital converters (ADCs) are often the focus of latency analyses in audio systems, while data buffering, digital signal processing tasks, other software processes, and even wireless transport can contribute to latency.

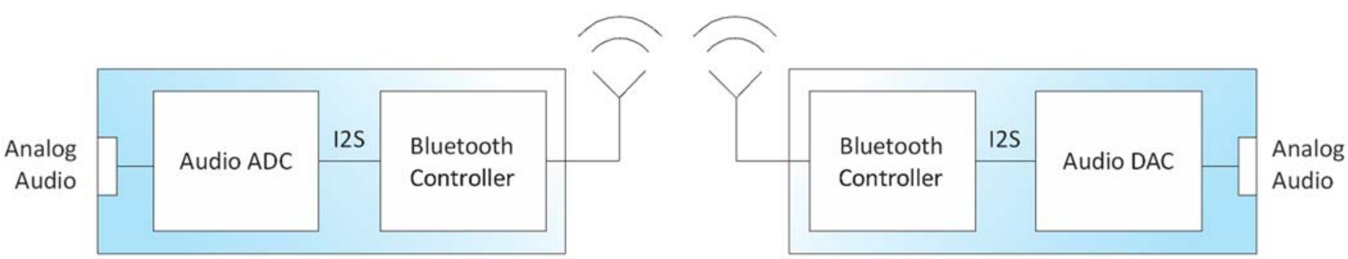

Figure 5 - Simple Audio System Block Diagram

Bluetooth Audio

Bluetooth presents a wide variety of applications for audio, ranging from BR/EDR (Classic Bluetooth) for telephony and music to newer approaches using Bluetooth Low Energy LE Audio and its solitary companion codec LC3, which supports both broadcast and unicast (connection-oriented) topologies.

These applications can address many use cases, such as a single user listening to multiple, synchronized streams, multiple users sharing the same broadcast, multiple users sharing different synchronized broadcasts (such as language-specific cases), bi-directional audio, and much more.

Figure 6 shows an Ellisys analyzer capture of many LE Audio streams. In this case, the LE Protocol Overview (filtered to show only Isochronous traffic) and the Spectrum view are also shown. The audio streams are indicated by the blue lines in the Audio view. This capture includes primarily broadcast isochronous streams (BIS) although there may be unicast streams or Classic Bluetooth audio included as well. In this case, these streams are captured over the air, but there may also be concurrent capture of time-synchronized analog and I2S digital streams input via the Audio Grabber or I2S digital streams captured directly via the analyzer's Logic port (these would also be represented in the Audio view). In addition, one or more audio streams carried over the HCI can be captured. Quite the systemic view!

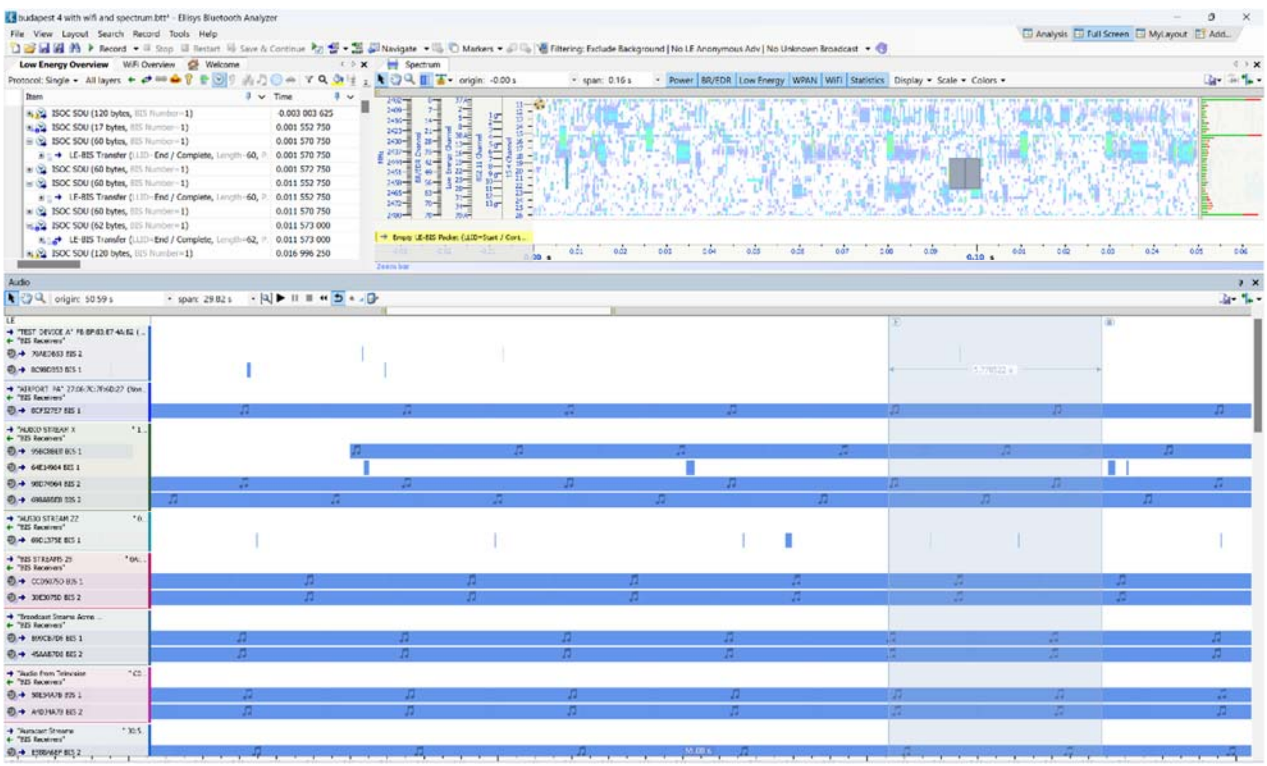

Figure 6 - Capture of Many Broadcast and Connected Streams

What is Inter-IC Sound?

I2S (Inter-IC Sound) is a relatively simple communications bus that is used to connect audio in a digital format (PCM) between integrated circuits, like DACs, ADCs, DSPs, buffers, etc. I2S is sometimes used as an external link between two audio devices, although there is no standard cable for this purpose, and this is not a common approach.

The I2S bus consists of a serial clock (SCK), a Word Select line (WS), sometimes called Frame Sync, where a LOW enables the left channel's data and a HIGH enables the right channel's data, and typically one multiplexed (stereo) serial data line (SD). The clock rate will be dependent on the sample rate, the number of bits used per channel, and the number of channels.

Use of Ellisys Bluetooth Analyzers by Audio Engineers

Ellisys Bluetooth analyzers are heavily used by audio engineers worldwide for a variety of functions, including characterizing audio quality, optimizing transmission characteristics, latency measurements, protocol debug of stack issues, retransmission characterizations, power and battery optimizations, wireless coexistence studies, and more.

Users can concurrently capture audio in many forms, including digital format (PCM I2S), over-the-air via Bluetooth and Wi-Fi, over the host controller interface (HCI), and with the Audio Grabber, via analog source(s). These various captures are all perfectly timed and presented to the user in various logical, textual, and graphical formats. Audio can be exported for further analysis in third-party applications as well, e.g., Audacity (free open-source audio editor, see https://www.audacityteam.org).

To get a sense of what an audio capture contains, look at Figure 7 below. This includes capture of Bluetooth over-the-air traffic, with concurrent capture of HCI traffic. Capturing audio on both sides of the controller can be quite useful. A device filter is applied to focus on the two communicating devices, and protocol filters are enacted on both traffic streams to further focus on audio. Command and audio streams are shown in the Audio view, which allows for playing the audio live during recording or on a saved capture, looping sections of the audio, timing measurements, time correlation to other views, and export to WAV files.

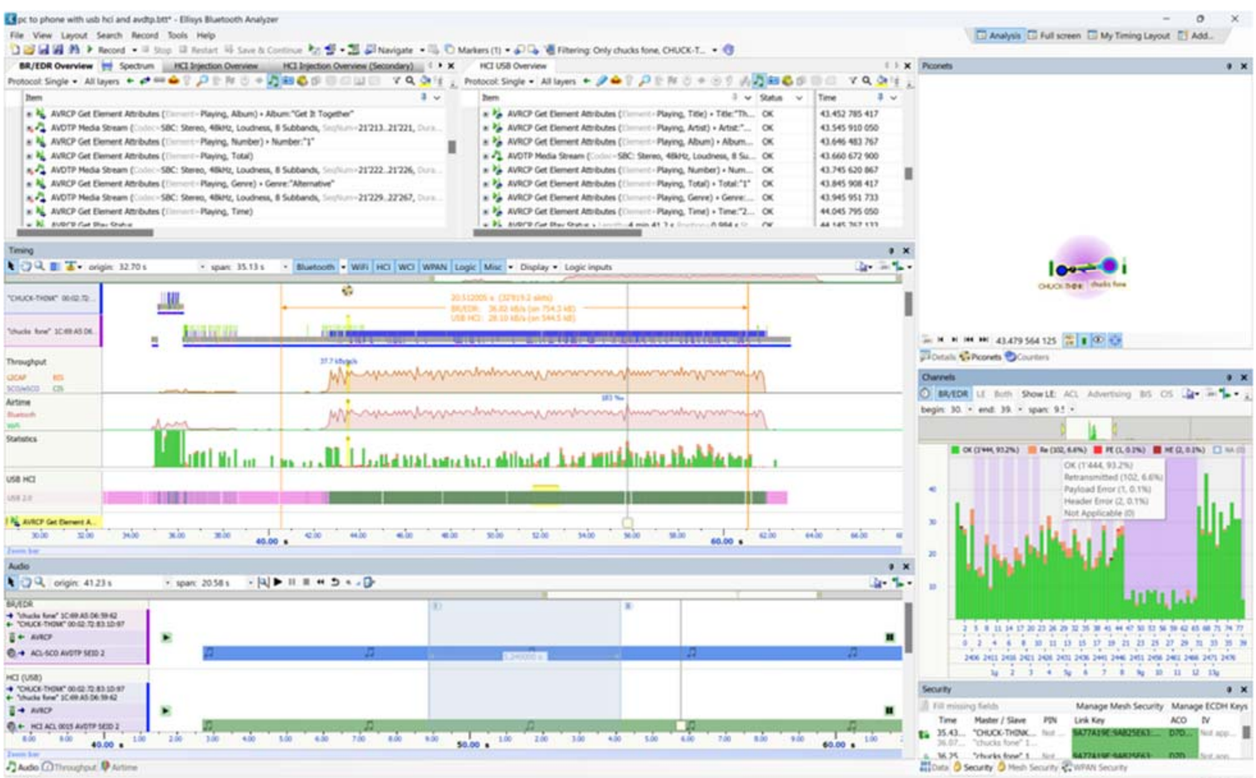

Figure 7 - Ellisys Audio Capture

The Channels view (bottom-right of Figure 7) indicates the per-channel quality of the capture, including dynamic avoidance of interferences, retransmissions, etc. Wi-Fi is also captured and is indicated in the Timing view, (the Wi-Fi Overview window is not shown). All streams are shown perfectly synchronized in the Timing view, along with throughput information, airtime utilization, and various statistics.

Ellisys analyzers include advanced, unique audio features, such as LC3 AutoDetect (standard feature) which involves a test-equipment-grade LC3 codec for improving LE audio capture quality, and tZERO™ Tracking (standard on Bluetooth Vanguard), a proprietary, high performance processing technology that allows for capture of the earliest instances isochronous traffic following encryption and capture of encrypted LE audio without having to pre-enter an LTK.

In Figure 8, we see a typical capture of multiple I2S digital streams, along with the clock (SCK) and word select (WS) lines. Two synchronized views are shown: the Timing view and the Audio view. These streams may be natively digital (as captured using the Flying Leads probe), or they may be representations of captured analog audio from the Audio Grabber's 3.5 mm jack or its MIC inputs.

Note the correlated time indications at the bottom of each view and the timing cursors, also populated into each view.

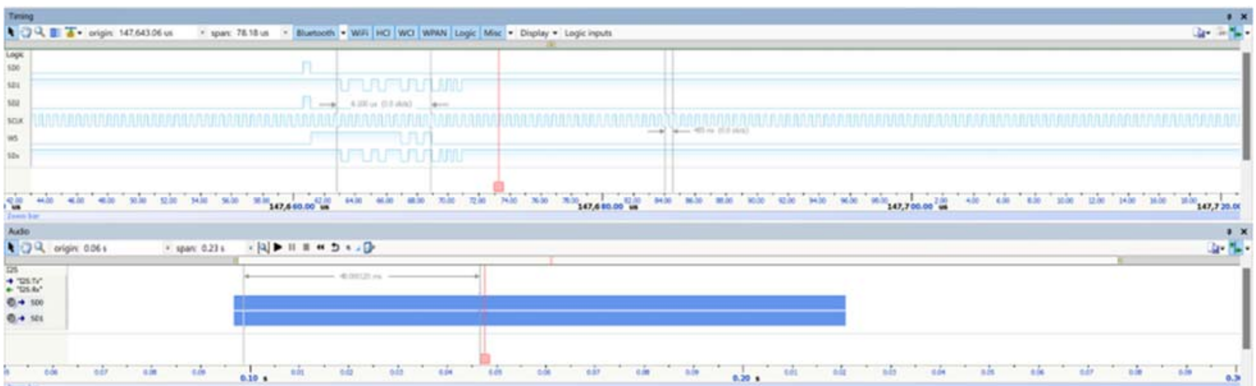

Figure 8 - Timing and Audio Views Showing Capture of Digital Audio Streams

Setting Up to Use the Audio Grabber

To set up the Audio Grabber, perform the following:

1. If the Audio Grabber is to be attached through the adapter (Figure 2), connect the Flying Leads probe (Figure 4), if needed, to the adapter, otherwise proceed to Step 2.

   Note: For Bluetooth Explorer units, the adapter *must* be used due to the mismatching size of the Logic connector on Explorer. For Bluetooth Tracker and Vanguard, it is optional. The adapter also allows for attachment of the Flying Leads probe, used for capture of additional I2S buses, other communications standards (e.g., UART, SPI, I2C SWD), and logic signals. See the section titled Flying Leads Probe – Bluetooth Tracker and Vanguard or Flying Leads Probe – Bluetooth Explorer for more information.

2. If using the Audio Grabber without the adapter, connect it to the Logic connector on the analyzer. If using the adapter, connect the Audio Grabber to the adapter (Figure 3), then attach the adapter to the Logic connector.

3. If the Flying Leads probe is used, attach the probe's lead(s) to the desired input(s), except for inputs 0, 1 and 2 which are dedicated to the Audio Grabber.

4. In Recording Options, assign primary Audio I2S inputs as shown in Figure 9. The analog inputs to the Audio Grabber are converted to I2S and are hardwired to I/Os 0 (SCK), 1 (WS), and 2 (SD0) as shown on the Audio Grabber PCB and as shown below in Figure 9. The Input Delay shall be set to 375 us.

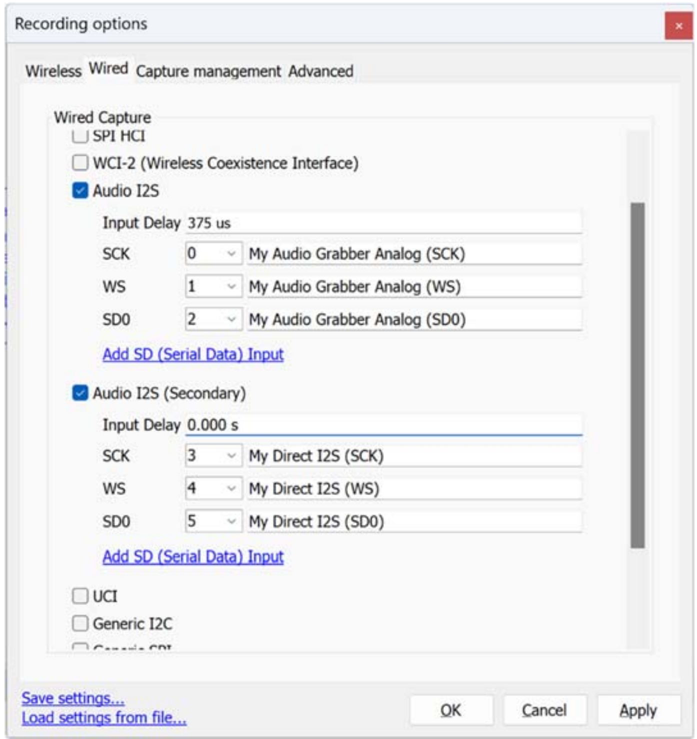

Figure 9 - Recording Options Setup for Audio I2S Inputs and Input Delay

Conveniently, an Input Delay is available in the Recording Options setup for Audio I2S. This setting is used to compensate for expected ADC latencies on the Audio Grabber. The ADC will have an expected latency when converting analog inputs to the digital I2S format used by the analyzer. As users want the time of the analog audio, not the time of the digital audio, the input delay compensates for this ADC latency, so that the timestamping displayed by the analyzer software will match the actual time of the analog audio. The Audio Grabber latency has been precisely characterized at 375 us.

The Audio Grabber configuration can be reviewed and edited from the analyzer tab of the About box accessible from the Help menu, by clicking the Configure link, as shown in Figure 10.

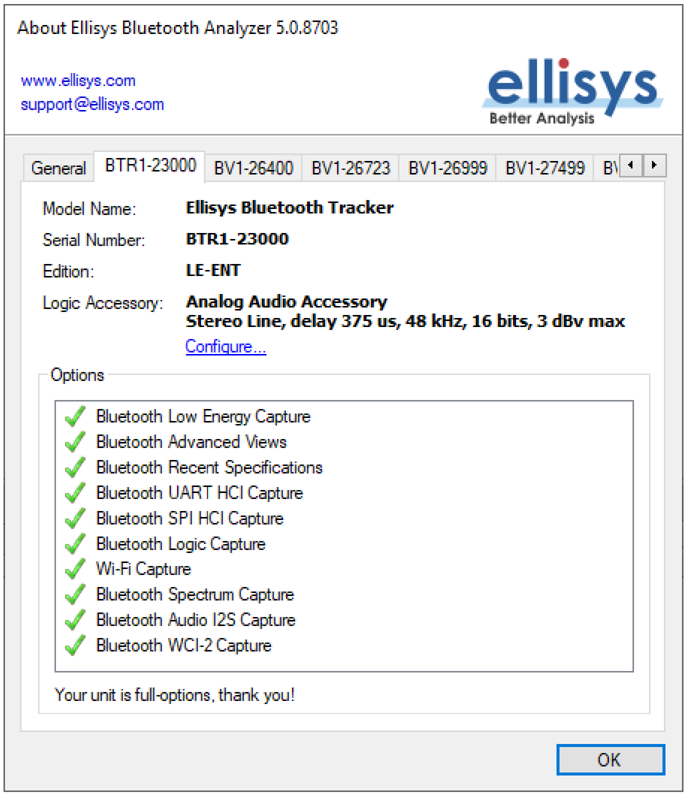

Figure 10 - Audio Grabber Configuration Menu in Help | About

There are currently four configurations from which to choose, shown in Figure 11, below. Select the desired configuration. This can be both Line IN inputs, both MIC inputs, or one of each.

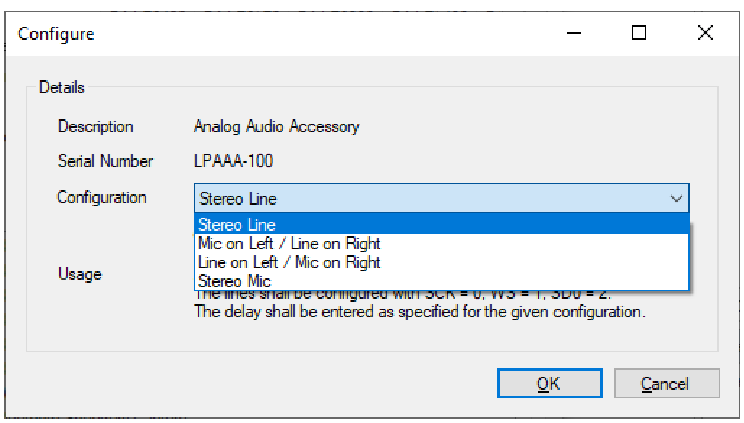

Figure 11 - Audio Grabber Configuration Dialog

Typical Latency Measurements

Without the Audio Grabber, the analyzer can still provide capture of digital audio streams (one or more). This is depicted in Figure 12.

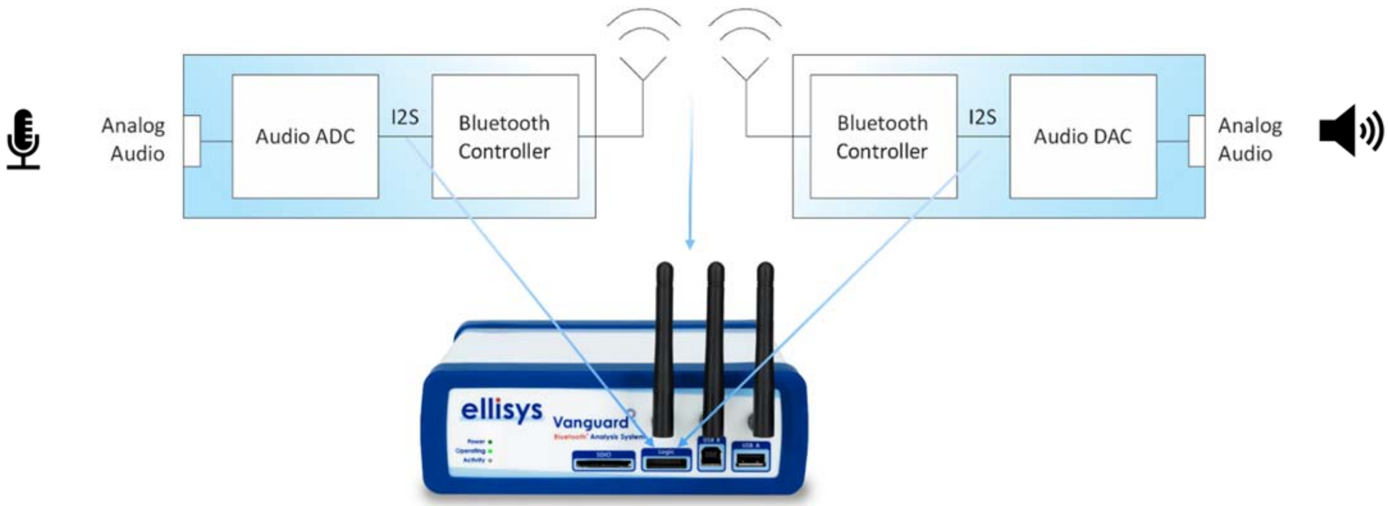

Figure 12 - Analyzer Setup to Capture Two Digital Audio Streams and Over-the-Air Traffic

With the Audio Grabber, *analog* audio can be added to the analysis, providing latency measurements, including through ADC and DAC components. See Figure 13, below.

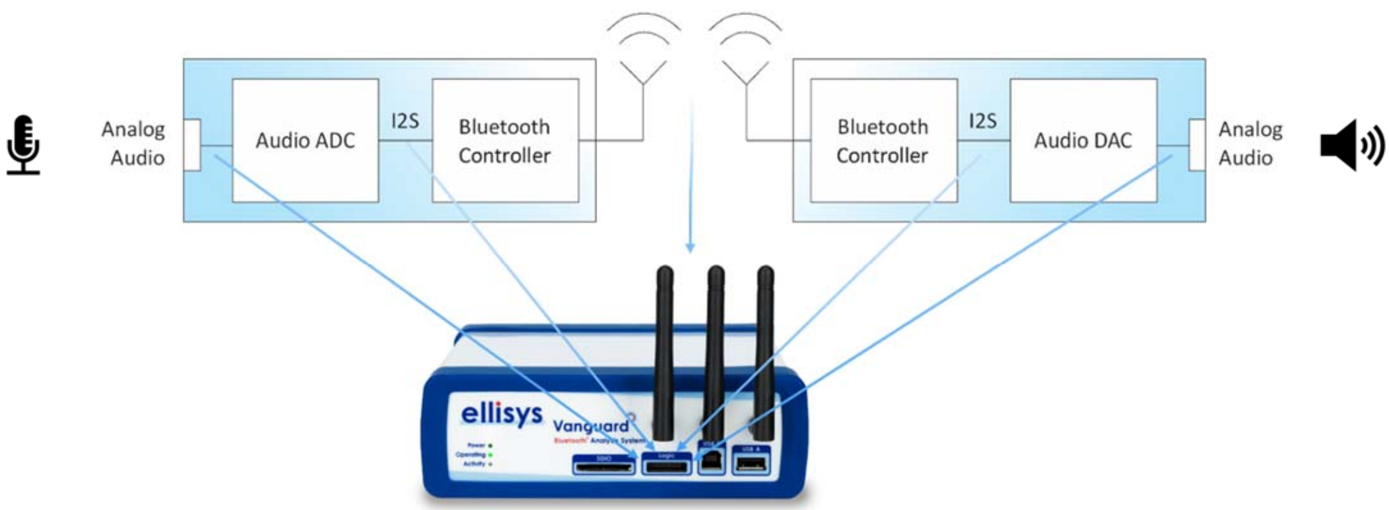

Figure 13 - Analyzer Setup to Capture Two Digital and Two Analog Audio Streams, and Over-the-Air Traffic

Exporting Audio

All audio streams captured by the analyzer can be exported from the File | Export menu as shown in Figure 14 below. Each captured audio stream will be individually exported to WAV format.

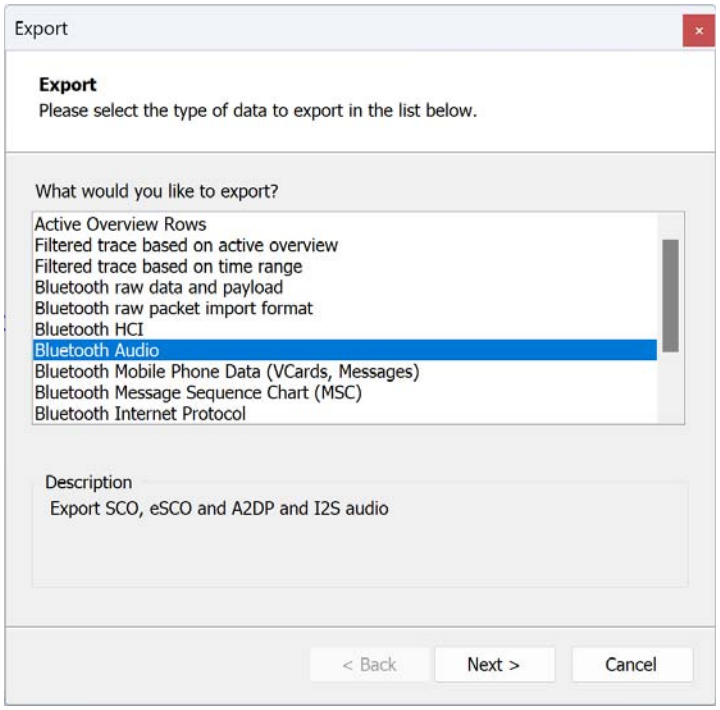

Figure 14 - Export Menu (Bluetooth Audio Selected)

Flying Leads Probe – Bluetooth Tracker and Vanguard

The Logic connection on the Bluetooth Tracker and Vanguard analyzers contains 20 pins (two rows of 10 pins), which mate with sockets on the mating connector of the Flying Leads probe.

The Flying Leads Probe is keyed for proper orientation to the Analyzer's Logic receptacle.

Figure 15 below illustrates the keyed female plug on the probe and the corresponding wire colors.

I/O 14	19	20	I/O 15
I/O 12	17	18	I/O 13
I/O 10	15	16	I/O 11
I/O 8	13	14	I/O 9
I/O 6	11	12	I/O 7
I/O 4	9	10	I/O 5
I/O 2	7	8	I/O 3
I/O 0	5	6	I/O 1
	3	4	
GND	1	2	

Figure 15- Pinout for Flying Leads Probe for Bluetooth Tracker and Vanguard

Figure 16 illustrates the keyed receptacle on the analyzer. N.C. = Not Connected.

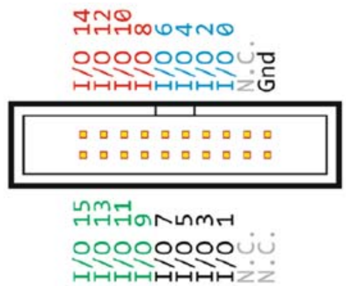

Figure 16 - Logic Receptacle on Bluetooth Tracker and Vanguard Analyzers

Flying Leads Probe – Bluetooth Explorer

The Logic connection on the Bluetooth Explorer analyzer contains 26 pins (two rows of 13 pins), which mate with sockets on the mating connector of the Flying Leads probe.

The Flying Leads Probe is keyed for proper orientation to the Analyzer's Logic receptacle.

Figure 17 below illustrates the keyed female plug on the probe and the corresponding wire colors.

	25	26	
Input 0	23	24	Input 8
Input 1	21	22	Input 9
Input 2	19	20	Input 10
Input 3	17	18	Input 11
GND	15	16	
Input 4	13	14	
Input 5	11	12	
Input 6	9	10	
Input 7	7	8	
GND	5	6	
	3	4	
	1	2	

Figure 17 - Pinout for Flying Leads Probe for Bluetooth Explorer

Figure 18 illustrates the keyed receptacle on the analyzer.

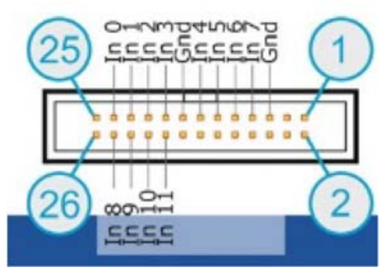

Figure 18 - Logic Receptacle on Bluetooth Explorer Analyzer