This document presents the Harpoon release 2.4 for i.MX 8M and i.MX 93 device family, using the Arm Cortex-A53/A55 processor (Armv8-A architecture).
1 Overview

This document presents the Harpoon release 2.4 for i.MX 8M and i.MX 93 device family, using the Arm Cortex-A53/A55 processor (Armv8-A architecture).

Harpoon provides an environment for developing real-time demanding applications on an RTOS running on one (or several) Cortex-A core(s) in parallel of a Linux distribution, leveraging the 64-bit Arm architecture for higher performance.

The system starts on Linux and the Jailhouse hypervisor partitions the hardware to run both Linux and the guest RTOS in parallel.

The hardware partitioning is configurable and depends on the use case. This release includes an audio application, an industrial application and a real-time latency measurement application, all available both for FreeRTOS as well as Zephyr (some application feature limitations exist depending on the selected platform and RTOS).

This release supports the following software and hardware:

- **NXP Linux Yocto**
  - i.MX LF 6.1.22-2.0.0: For more information, see the [i.MX Yocto Project User’s Guide](#).
  - Real-time Edge SW v2.6: For more information, see the [Real-time Edge Yocto Project v2.6 User Guide](#).
- **i.MX 8M Series**
  - i.MX 8M Mini LPDDR4 EVKB
  - i.MX 8M Nano LPDDR4 EVK
  - i.MX 8M Plus LPDDR4 EVK
- **i.MX 9 Series**
  - i.MX 93 EVK
- **Jailhouse hypervisor**
- **FreeRTOS V10.5.0 kernel**
  - Guest OS running on Jailhouse cell
- **Zephyr RTOS 3.3.0**
  - Cortex-A53 and Cortex-A55 port, SMP
  - Guest OS running on Jailhouse cell
- **MCUXpresso SDK 2.13.1**
  - GIC, Timer and MMU AARCH64 drivers
  - FlexCAN, ENET, ENET_QOS, GPT, TPM, I2C, SAI, LPUART, and UART SoC drivers
  - Audio Codec drivers
  - PHY drivers
- **RTOS applications**
  - Audio reference application
  - Industrial reference application
  - Real-time latency measurement application
  - Virtio Networking reference application
  - Hello World application
### 1.1 Supported Features

Table 1. Harpoon 2.4 supported features

<table>
<thead>
<tr>
<th>Feature</th>
<th>i.MX 8M Mini</th>
<th>i.MX 8M Nano(^1)</th>
<th>i.MX 8M Plus</th>
<th>i.MX 93</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peripherals</strong></td>
<td></td>
<td></td>
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<tr>
<td>GICv3</td>
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<td>MMU</td>
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<tr>
<td>UART</td>
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<td>LPUART</td>
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<td>GPT</td>
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<tr>
<td>TPM</td>
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<tr>
<td>I(^2)C</td>
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<tr>
<td>SAI</td>
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<tr>
<td>ENET</td>
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<tr>
<td>ENET_QOS</td>
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<tr>
<td>Audio Codec(s)</td>
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<tr>
<td>Ethernet PHY(s)</td>
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<tr>
<td><strong>MiddleWare</strong></td>
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<tr>
<td>GenAVB/TSN</td>
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<tr>
<td>RPMsg-Lite</td>
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<tr>
<td><strong>Audio Application</strong></td>
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<tr>
<td>SAI pipeline(s)</td>
<td>•</td>
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<tr>
<td>AVB pipeline</td>
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<tr>
<td>AVB pipeline (with MCR)</td>
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<tr>
<td>SMP pipeline</td>
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<tr>
<td><strong>Industrial Application</strong></td>
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<tr>
<td>CAN</td>
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<tr>
<td>Ethernet</td>
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<tr>
<td>TSN</td>
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<tr>
<td><strong>Real-time Latency Application</strong></td>
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<tr>
<td><strong>Virtio Networking Application(^3)</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hello World Application</strong></td>
<td>•</td>
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<td>•</td>
<td>•</td>
</tr>
</tbody>
</table>

\(^{[1]}\) i.MX Linux Yocto based image only
\(^{[2]}\) Using ENET interface without 802.1Qbv support
\(^{[3]}\) Real-time Edge based image only

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1.2 Architecture

The following figure shows the architecture of the Harpoon solution.

The bottom box shows the hardware partitioning between Jailhouse cells.

The boxes in dark orange (group 1) show the main hardware blocks allocated to the Linux OS.

The boxes in blue (group 3) show the main hardware blocks allocated to the RTOS.

The boxes in light orange (group 2) show the main hardware blocks shared between Linux and the RTOS.

Harpoon-apps is the real-time application running on Jailhouse's inmate cell. It is built on top of Zephyr or FreeRTOS, using MCUXpresso drivers.

1.3 Hardware resource partitioning

Jailhouse hypervisor is used to run an RTOS in parallel with Linux: FreeRTOS and Zephyr are supported in this release.

Jailhouse is a simple hypervisor that assigns hardware resources to a guest OS instead of virtualising them. For instance, a CPU core is statically assigned to a specific guest and is not shared with other guests.

In Jailhouse terms, the RTOS (inmate) runs in a cell. A configuration file describes which hardware resources are assigned to this cell. This configuration file contains descriptions of the following:

- CPU cores assigned to the cell
- Interrupt lines assigned to the cell
- Memory regions assigned to the cell
- Virtual PCI devices used for communication between cells

There is also a root cell configuration that describes the hardware prior to the hardware partitioning.

The source files of the cell configurations are embedded through patches in the Jailhouse recipe of the Harpoon meta-layer, at the following locations:

- `configs/arm64/imx8m*-harpoon-freertos.c` for the cell configuration of the FreeRTOS hello_world and rt_latency use case
• configs/arm64/imx8m*-harpoon-zephyr.c for the cell configuration of the Zephyr hello_world and rt_latency use case
• configs/arm64/imx8m*-harpoon-freertos-audio.c for the cell configuration of the FreeRTOS audio use case
• configs/arm64/imx8m*-harpoon-freertos-avb.c for the cell configuration of the FreeRTOS audio (AVB) use case
• configs/arm64/imx8m*-harpoon-freertos-virtio.c for the cell configuration of the FreeRTOS Virtio Networking use case
• configs/arm64/imx8m*-harpoon-zephyr-audio.c for the cell configuration of the Zephyr audio use case
• configs/arm64/imx8m*-harpoon-freertos-industrial.c for the cell configuration of the FreeRTOS industrial use case
• configs/arm64/imx8m*-harpoon-zephyr-industrial.c for the cell configuration of the Zephyr industrial use case
• configs/arm64/imx93-harpoon-freertos.c for the cell configuration of the FreeRTOS hello_world and rt_latency use case
• configs/arm64/imx93-harpoon-freertos-virtio.c for the cell configuration of the FreeRTOS Virtio Networking use case
• configs/arm64/imx93-harpoon-zephyr.c for the cell configuration of the Zephyr hello_world and rt_latency use case
• configs/arm64/imx8m*.c and configs/arm64/imx93.c for the root cell configuration

The CPU core allocated to the RTOS forms a bitmap in the cpu structure. Here, CPU core 3 is assigned to the cell:

```c
.cpus = {
    0b1000,
},
```

For a multicore (SMP) cell, two cores can be used, for instance:

```c
.cpus = {
    0b1100,
},
```

Memory regions assigned to the inmate cell are listed in the mem_regions structure. Memory regions can be reserved for the inmate cell or shared with the Linux root cell.

Memory regions can be DDR chunks for the inmate cell use as well as device memory mapped regions such as UART or SAI.

Interrupts are mapped to the cell with the irqchips structure.

Virtual PCI devices are defined with the pci_devices structure. These virtual devices are used by Jailhouse to implement IVSHMEM v2 communication channels.

## 2 Building Harpoon Yocto images

As mentioned in the overview section, Harpoon is compatible with both i.MX Yocto and Real-Time Edge Yocto. Each distribution is addressed in a separate section below.
2.1 i.MX Yocto

To build this release, fetch its Yocto manifest and get the meta-layers:

```bash
$ mkdir yocto
$ cd yocto
$ repo init -u https://github.com/nxp-imx/imx-manifest -b imx-linux-mickledore -m imx-6.1.22-2.0.0_harpoon-v2.xml
$ repo sync
```

Then, prepare the environment with the following command:

```bash
$ DISTRO=fsl-imx-xwayland MACHINE=<machine> source imx-harpoon-setup-release.sh -b build.<machine>
```

Where, `<machine>` is one of the following:

- `imx8mm-lpddr4-evk` for i.MX 8M Mini EVKB board
- `imx8mn-lpddr4-evk` for i.MX 8M Nano EVKB board
- `imx8mp-lpddr4-evk` for i.MX 8M Plus EVK board
- `imx93evk` for i.MX 93 EVK board

The end user license agreement must be accepted to continue.

Then build the image with the following command:

```bash
$ bitbake imx-image-core
```

The image is then available in subdirectory `tmp/deploy/images/<machine>/`

Copy the disk image to a micro-SD card. For example, assuming the card is recognized as `/dev/mmcblk0` by your host machine:

```bash
$ zstdcat imx-image-core-<machine>.wic.zst | sudo dd of=/dev/mmcblk0 bs=1M
```

The micro-SD card now contains the release.

2.2 Real-Time Edge Yocto

See the [Real-time Edge Yocto Project User Guide](#) to build Harpoon and prepare an SD card for supported boards.

3 Hardware Setup

3.1 i.MX Reference Boards

This Harpoon release supports the following development boards.
3.1.1 i.MX 8M Mini EVK

![Figure 2. i.MX 8M Mini EVK](image)

**Note:** For more information to order the board, see [https://www.nxp.com/design/development-boards/i-mx-evaluation-and-development-boards/evaluation-kit-for-the-i-mx-8m-mini-applications-processor:8MMINILPD4-EVK](https://www.nxp.com/design/development-boards/i-mx-evaluation-and-development-boards/evaluation-kit-for-the-i-mx-8m-mini-applications-processor:8MMINILPD4-EVK)

3.1.2 i.MX 8M Nano EVK

![Figure 3. i.MX 8M Nano EVK](image)

**Note:** For more information to order the board, see [https://www.nxp.com/design/development-boards/i-mx-evaluation-and-development-boards/evaluation-kit-for-the-i-mx-8m-nano-applications-processor:8MNANOD4-EVK](https://www.nxp.com/design/development-boards/i-mx-evaluation-and-development-boards/evaluation-kit-for-the-i-mx-8m-nano-applications-processor:8MNANOD4-EVK).
3.1.3 i.MX 8M Plus EVK

Figure 4. i.MX 8M Plus EVK

Note: For more information to order the board, see https://www.nxp.com/design/development-boards/i-mx-evaluation-and-development-boards/i-mx-8m-plus-evaluation-kit-enabling-power-measurement:8MPLUSLPD4-PEVK.

3.1.4 i.MX 93 EVK

Figure 5. i.MX 93 Plus EVK

Note: For more information to order the board, see https://www.nxp.com/design/development-boards/i-mx-evaluation-and-development-boards/i-mx-93-evaluation-kit:i.MX93EVK.

3.2 Audio use case hardware

Harpoon audio application uses the I2S HiFiBerry audio card DAC+ ADC Pro.
HiFiBerry DAC+ ADC Pro is an audio card designed for the Raspberry Pi, but it can be connected to EVK boards using the 40-pin connector, provided a few adaptations are made.

The following pins on the EVK's 40-pin connector must be connected to the following HiFiBerry's pins.

<table>
<thead>
<tr>
<th>EVK</th>
<th>HiFiBerry</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>5V</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>I2C SDA</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>I2C SCK</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>GND</td>
</tr>
<tr>
<td>35</td>
<td>40</td>
<td>I2S TX</td>
</tr>
<tr>
<td>36</td>
<td>12</td>
<td>I2S clock</td>
</tr>
<tr>
<td>37</td>
<td>35</td>
<td>I2S word select for RX and TX</td>
</tr>
<tr>
<td>38</td>
<td>38</td>
<td>I2S RX</td>
</tr>
</tbody>
</table>

Table 2. EVK - HiFiBerry transposition

Note: For more information to order the board, see https://www.hifiberry.com/shop/boards/hifiberry-dac-adc-pro/
A complete setup, with a handmade transposer to respect above pinout, is shown as follows.
The audio card has both an ADC (PCM1863) to record audio and a DAC (PCM5122) for audio playback. Record is done through the audio jack (connector highlighted in 1 in the following figure) and playback is done through the RCA connectors (highlighted in 2).

Control of the PCM1863 is done through I2C3, at address 0x4a. Control of the PCM5122 is done through I2C3, at address 0x4d.

Note: For more information to order the board, see https://www.hifiberry.com/shop/boards/hifiberry-dac-adc-pro/.
Both the PCM1863 and PCM5122 use i.MX I2S5. The I2S5 is the I2S clock master. Two oscillators (one for sampling frequencies multiple of 44,100 Hz, one for sampling frequencies multiple of 48,000 Hz) are present on the HiFiBerry card, and controlled by PCM5122 GPIOs.

The following diagram shows the HiFiBerry architecture.

![HiFiBerry Architecture Diagram](image)

The PCM1863 and the PCM5122 use the same signal for I2S word select by using SAI synchronous mode.

### 3.3 Industrial use case hardware

Harpoon's industrial application may use the following hardware depending on the use case.
Figure 12. LS1028A AVB/TSN network bridge

**Note:** For more information to order the board, see [https://www.nxp.com/design/qorIQ-developer-resources/layerscape-ls1028a-reference-design-board:LS1028ARDB](https://www.nxp.com/design/qorIQ-developer-resources/layerscape-ls1028a-reference-design-board:LS1028ARDB).

The LS1028A RDB is used as a TSN bridge/switch in a TSN network to demonstrate the TSN Ethernet use case running from the inmate cell.
3.4 Virtio networking use case hardware

User needs to connect **ENET port** on i.MX 8M Mini EVK / i.MX 8M Plus EVK / i.MX 93 EVK to another board/PC or network switch/router to make sure the networking link is up before running Harpoon Virtio networking use case.

4 Running Harpoon Reference Applications

4.1 Basic setup

The EVK boards expose serial ports through their USB debug interface. One of these serial ports is used by Linux for its console, and another one is used by the guest RTOS.

To run the reference applications, open both serial ports with terminal emulators, insert the micro-SD card on which the Yocto image has been flashed in the EVK and power up the board.

4.2 Starting Linux kernel

Linux kernel must be started with a (Harpoon specific) Jailhouse compatible device tree.

To do this, when U-Boot is executing, stop at U-Boot prompt with a terminal emulator connected to the serial port and execute the following command (based on the board and the application):
• For i.MX 8M Mini (hello_world, audio or rt_latency):
  u-boot => setenv jh_root_dtb imx8mm-evk-harpoon.dtb
  u-boot => run jh_mmcboot

• For i.MX 8M Mini (hello_world or audio AVB):
  u-boot => setenv jh_root_dtb imx8mm-evk-harpoon-avb.dtb
  u-boot => run jh_mmcboot

• For i.MX 8M Mini (hello_world, industrial or rt_latency):
  u-boot => setenv jh_root_dtb imx8mm-evk-harpoon-industrial.dtb
  u-boot => run jh_mmcboot

• For i.MX 8M Mini (hello_world or virtio networking):
  u-boot => setenv jh_root_dtb imx8mm-evk-harpoon-virtio-net.dtb
  # Clear VirtIO magic value in memory in case of warm reboot to avoid MMIO probe error.
  u-boot => mw b8400000 0 1
  u-boot => run jh_mmcboot

• For i.MX 8M Nano (hello_world, audio or rt_latency):
  u-boot => setenv jh_root_dtb imx8mn-evk-harpoon.dtb
  u-boot => run jh_mmcboot

• For i.MX 8M Nano (hello_world or audio AVB):
  u-boot => setenv jh_root_dtb imx8mn-evk-harpoon-avb.dtb
  u-boot => run jh_mmcboot

• For i.MX 8M Nano (hello_world, industrial or rt_latency):
  u-boot => setenv jh_root_dtb imx8mn-evk-harpoon-industrial.dtb
  u-boot => run jh_mmcboot

• For i.MX 8M Plus (hello_world, audio or rt_latency):
  u-boot => setenv jh_root_dtb imx8mp-evk-harpoon.dtb
  u-boot => run jh_mmcboot

• For i.MX 8M Plus (hello_world or audio AVB):
  u-boot => setenv jh_root_dtb imx8mp-evk-harpoon-avb.dtb
  u-boot => run jh_mmcboot

• For i.MX 8M Plus (hello_world, industrial or rt_latency):
  u-boot => setenv jh_root_dtb imx8mp-evk-harpoon-industrial.dtb
  u-boot => run jh_mmcboot

• For i.MX 8M Plus (hello_world or virtio networking):
  u-boot => setenv jh_root_dtb imx8mp-evk-harpoon-virtio-net.dtb
  # Clear VirtIO magic value in memory in case of warm reboot to avoid MMIO probe error.
  u-boot => mw fc700000 0 1
  u-boot => run jh_mmcboot

• For i.MX 93 (hello_world or rt_latency):
  u-boot => setenv jh_root_dtb imx93-11x11-evk-harpoon.dtb
  u-boot => run jh_mmcboot
• For i.MX 93 (hello_world or virtio networking):

```
  u-boot => setenv jh_root_dtb imx93-11x11-evk-harpoon-virtio-net.dtb
  # Clear VirtIO magic value in memory in case of warm reboot to avoid MMIO probe error.
  u-boot => mw fc700000 0 1
  u-boot => run jh_mmcboot
```

**Note:** This configuration is not persistent after a reboot.

To make changes permanent, execute the following commands once (after `setenv` above):

```
  u-boot => setenv bootcmd 'run jh_mmcboot'
  u-boot => saveenv
```

Now, at each reboot, the system starts with the Jailhouse compatible configuration and no user interaction is required.

4.3 hello_world application

The hello_world application is a simple demo for the basic features like IRQ, generic timer and UART on FreeRTOS and Zephyr.

The application binary is available in the Harpoon share directory of the root file system:

```
/usr/share/harpoon/inmates/freertos/hello_world.bin # FreeRTOS binary
/usr/share/harpoon/inmates/zephyr/hello_world.bin # Zephyr binary
```

To use the hello_world application, Jailhouse must be started first. To start Jailhouse and the application, create the corresponding Harpoon configuration file and run the harpoon service using `systemd`, for instance:

To run FreeRTOS binary, create configuration:

```
# harpoon_set_configuration.sh freertos hello
```

To run Zephyr binary, create configuration:

```
# harpoon_set_configuration.sh zephyr hello
```

Start Harpoon service:

```
# systemctl start harpoon
```

The configuration file is stored under `/etc/harpoon/harpoon.conf`, the Harpoon systemd service uses it to start Jailhouse and the application.

Once the Harpoon service has been started, the following logs is shown in the inmate cell console:

FreeRTOS logs:

```
INFO: hello_func            : Hello world.
tic tac tic tac ...
```

Zephyr logs:

```
*** Booting Zephyr OS build zephyr-v3.3.0-25-gd3644304707e ***
INFO: hello_func            : Hello world.
INFO: hello_func            : 2 threads running
```
4.4 Audio application

4.4.1 Features of the audio application

The audio application is available in the harpoon share directory of the target's root file system:

<table>
<thead>
<tr>
<th>Path</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>/usr/share/harpoon/inmates/freertos/audio.bin</td>
<td>FreeRTOS binary</td>
</tr>
<tr>
<td>/usr/share/harpoon/inmates/zephyr/audio.bin</td>
<td>Zephyr binary</td>
</tr>
</tbody>
</table>

The different modes are:

- **DTMF playback**: plays a DTMF sequence.
- **Sine wave playback**: plays a generated sine wave.
- **Loopback**: record sound from HiFiBerry's input and play it live through HiFiBerry's output.
- **Full Audio pipeline**: implements a flexible 3-stage pipeline with different sources (DTMF, sine waves, SAI input) that can be routed to different sinks (SAI outputs).
- **AVB Audio pipeline (FreeRTOS only)**: implements a 3-stage pipeline with AVB input as a source that can be routed to different sinks (SAI outputs, AVTP sink).
- **AVB Audio pipeline (FreeRTOS only) with Media Clock Recovery support**: uses the above pipeline only with elements that support Media Clock Recovery.
- **SMP Audio pipeline (Zephyr only)**: splits the Full Audio pipeline in two pieces to process them onto different cores.

All the modes support (see Notes for exceptions):

- Basic pipeline framework for audio processing
- 44100, 48000, 88200, 96000, 176400, and 192000 Hz sample frequencies
- Audio processing period with 2, 4, 8, 16, or 32 frames
- Audio processing in 64bit float format
- Audio playback to both SAI3 (on board codec/sound jack) and SAI5 (HiFiBerry)
- Audio capture from SAI5 (HiFiBerry)

**Note:**
- **Playback on SAI3**: The i.MX 8M Plus EVK on board codec (WM8960) supports sample rates up to 48 kHz only. 88.2 kHz and above frequency settings will fail for this codec.
- **Media Clock Recovery**: Only supported on i.MX 8M Plus EVK using SAI3 (onboard jack)

4.4.2 Starting the audio application

The Harpoon service uses the `/etc/harpoon/harpoon.conf` configuration file that contains the RTOS and the application to run. By default, the configuration file points to the FreeRTOS audio application. To use the Zephyr audio application, the following command can be run to generate an appropriate configuration file:

```bash
# harpoon_set_configuration.sh zephyr audio
```

To use the audio application, Jailhouse must be started first. To start Jailhouse and the audio application, run the Harpoon service with systemd:

```bash
# systemctl start harpoon
```
Once the Harpoon service has been started, `harpoon_ctrl` is used to start or stop the audio modes with optional parameters. The different options for the audio application are:

<table>
<thead>
<tr>
<th>Audio options:</th>
</tr>
</thead>
<tbody>
<tr>
<td>-f &lt;frequency&gt;  audio clock frequency (in Hz)</td>
</tr>
<tr>
<td>Supporting 44100, 48000, 88200, 176400, 96000, 192000 Hz</td>
</tr>
<tr>
<td>Will use default frequency 48000Hz if not specified</td>
</tr>
<tr>
<td>-p &lt;frames&gt;  audio processing period (in frames)</td>
</tr>
<tr>
<td>Supporting 2, 4, 8, 16, 32 frames</td>
</tr>
<tr>
<td>Will use default period 8 frames if not specified</td>
</tr>
<tr>
<td>-r &lt;id&gt;  run audio mode id:</td>
</tr>
<tr>
<td>0 - dtmf playback</td>
</tr>
<tr>
<td>1 - sine wave playback</td>
</tr>
<tr>
<td>2 - playback &amp; recording (loopback)</td>
</tr>
<tr>
<td>3 - audio pipeline</td>
</tr>
<tr>
<td>4 - AVB audio pipeline</td>
</tr>
<tr>
<td>5 - SMP audio pipeline</td>
</tr>
<tr>
<td>6 - AVB audio pipeline (with MCR support)</td>
</tr>
<tr>
<td>-s  stop running audio mode</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Audio pipeline options:</th>
</tr>
</thead>
<tbody>
<tr>
<td>-a &lt;pipeline_id&gt;  audio pipeline id (default 0)</td>
</tr>
<tr>
<td>-d  audio pipeline dump</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Audio element options:</th>
</tr>
</thead>
<tbody>
<tr>
<td>-a &lt;pipeline_id&gt;  audio pipeline id (default 0)</td>
</tr>
<tr>
<td>-d  audio element dump</td>
</tr>
<tr>
<td>-e &lt;element_id&gt;  audio element id (default 0)</td>
</tr>
<tr>
<td>-t &lt;element_type&gt;  audio element type (default 0):</td>
</tr>
<tr>
<td>0 - dtmf source</td>
</tr>
<tr>
<td>1 - routing</td>
</tr>
<tr>
<td>2 - sai sink</td>
</tr>
<tr>
<td>3 - sai source</td>
</tr>
<tr>
<td>4 - sine source</td>
</tr>
<tr>
<td>5 - avtp source</td>
</tr>
<tr>
<td>6 - avtp sink</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Routing audio element options:</th>
</tr>
</thead>
<tbody>
<tr>
<td>-a &lt;pipeline_id&gt;  audio pipeline id (default 0)</td>
</tr>
<tr>
<td>-c  connect routing input/output</td>
</tr>
<tr>
<td>-d  disconnect routing input/output</td>
</tr>
<tr>
<td>-e &lt;element_id&gt;  routing element id (default 0)</td>
</tr>
<tr>
<td>-i &lt;input_id&gt;  routing element input (default 0)</td>
</tr>
<tr>
<td>-o &lt;output_id&gt;  routing element output (default 0)</td>
</tr>
</tbody>
</table>

### 4.4.3 Audio latency in loopback mode

The loopback mode reads audio samples from HiFiBerry's ADC in an audio buffer and sends this buffer to the HiFiBerry's DAC when fully loaded.

The end-to-end latency, between the analog audio input and the analog audio output, has been measured and is dependent on the audio buffer size and the audio sampling rate. The RTOS and SoC combination does not alter the latency measurements.

<table>
<thead>
<tr>
<th>Sampling rate (kHz)</th>
<th>Audio latency (μs)</th>
<th>Audio buffer size (frames)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.4.4 Running audio application: examples

4.4.4.1 Playing DTMF

To start DTMF playback with default parameters (48000 Hz sampling rate):

```bash
# harpoon_ctrl audio -r 0
```

The DTMF is played both to the HiFiBerry RCA outputs as well as the onboard jack.

To run another audio use case, the playback must be stopped with the following command:

```bash
# harpoon_ctrl audio -s
```

4.4.4.2 Playing in loopback mode

In loopback mode, the SAI input is copied to the SAI output.

To start loopback mode with default parameters (48000 Hz sampling rate, 8 frame period size):

```bash
# harpoon_ctrl audio -r 2
```

To run another audio use case, the playback must be stopped with the following command:

```bash
# harpoon_ctrl audio -s
```

4.4.4.3 Playing a full audio pipeline

The reference audio application is based on a basic pipeline framework for audio processing. Different audio processing elements can be assembled in a pipeline to process audio from source(s) to sink(s). The pipeline is processed in real time, cyclically with a fixed period.

In the audio pipeline mode there is a three stage pipeline composed of a routing element in stage 2 which can link source elements from stage 1 to sink elements from stage 3.
When running the audio pipeline, the routes can be configured dynamically with the `harpoon_ctrl` command. This command uses source and sink indexes to connect elements.

Table 4. Indexes of source elements

<table>
<thead>
<tr>
<th>Index</th>
<th>Source element</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>DTMF, sequence 1</td>
<td>Software generated source</td>
</tr>
<tr>
<td>1</td>
<td>DTMF, sequence 2</td>
<td>Software generated source</td>
</tr>
<tr>
<td>2</td>
<td>Sine wave, 440 Hz</td>
<td>Software generated source</td>
</tr>
<tr>
<td>3</td>
<td>Sine wave, 880 Hz</td>
<td>Software generated source</td>
</tr>
<tr>
<td>4</td>
<td>SAI5, left channel</td>
<td>Hardware source</td>
</tr>
<tr>
<td>5</td>
<td>SAI5, right channel</td>
<td>Hardware source</td>
</tr>
<tr>
<td>6</td>
<td>SAI3, left channel</td>
<td>Hardware source</td>
</tr>
<tr>
<td>7</td>
<td>SAI3, right channel</td>
<td>Hardware source</td>
</tr>
</tbody>
</table>

Table 5. Indexes of sink elements

<table>
<thead>
<tr>
<th>Index</th>
<th>Sink element</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>SAI5, left channel</td>
<td>Hardware sink</td>
</tr>
<tr>
<td>1</td>
<td>SAI5, right channel</td>
<td>Hardware sink</td>
</tr>
<tr>
<td>2</td>
<td>SAI3, left channel</td>
<td>Hardware sink</td>
</tr>
<tr>
<td>3</td>
<td>SAI3, right channel</td>
<td>Hardware sink</td>
</tr>
</tbody>
</table>
This makes for a flexible pipeline. For instance, the following commands starts the pipeline and configures the routing element to have a loopback between SAI5 input and SAI3 output (i.e., sound recorded by the HiFiBerry card played by the EVK's internal codec) while a DTMF sequence is played on the left channel of SAI5's output and a 440 Hz sine wave on the right channel of SAI5's output (i.e., HiFiBerry's output):

```
# harpoon_ctrl audio -r 3             # start audio pipeline
# harpoon_ctrl routing -i 4 -o 2 -c   # SAI5's input to SAI3's output (L)
# harpoon_ctrl routing -i 5 -o 3 -c   # SAI5's input to SAI3's output (R)
# harpoon_ctrl routing -i 0 -o 0 -c   # DTMF to SAI5's output (L)
# harpoon_ctrl routing -i 2 -o 1 -c   # sinewave 440Hz to SAI5's output (R)
```

**Note:** The pipeline dump also outputs the Audio Buffer Routing for an easier Buffer Routing through the "Routing element".

### 4.4.4.4 Playing an AVB audio pipeline

The AVB audio pipeline embeds - as a source element - an AVB Listener, making use of the GenAVB/TSN stack streaming API's. This element is only responsible of the audio data path:

- Supports one or more AVTP Listener streams
- Supports one or more AVTP Talker streams
- Supports multi-channel AVTP streams
- Supports scatter of audio data
- Supports audio format conversion, from AVTP stream format to the common format
- Supports Media Clock Recovery (on a specific audio Pipeline)

It re-uses the audio application's pipeline framework for audio processing in which an AVTP Listener is added as a source.
AVB Audio pipeline showing the AVTP Listener with multiple streams as a source.

Figure 15. AVB Audio pipeline

When running the AVB audio pipeline, the routes can be configured dynamically with the `harpoon_ctrl` command. This command uses source and sink indexes to connect elements.

### Table 6. Indexes of source elements

<table>
<thead>
<tr>
<th>Index</th>
<th>Source element</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Sine wave, 440 Hz</td>
<td>Software generated source</td>
</tr>
<tr>
<td>1</td>
<td>SAI5, left channel</td>
<td>Hardware source</td>
</tr>
<tr>
<td>2</td>
<td>SAI5, right channel</td>
<td>Hardware source</td>
</tr>
<tr>
<td>3</td>
<td>SAI3, left channel</td>
<td>Hardware source</td>
</tr>
<tr>
<td>4</td>
<td>SAI3, right channel</td>
<td>Hardware source</td>
</tr>
<tr>
<td>5</td>
<td>AVTP, stream#0 left channel</td>
<td>AVB source from network</td>
</tr>
<tr>
<td>6</td>
<td>AVTP, stream#0 right channel</td>
<td>AVB source from network</td>
</tr>
<tr>
<td>7</td>
<td>AVTP, stream#1 left channel</td>
<td>AVB source from network</td>
</tr>
<tr>
<td>8</td>
<td>AVTP, stream#1 right channel</td>
<td>AVB source from network</td>
</tr>
</tbody>
</table>

### Table 7. Indexes of sink elements

<table>
<thead>
<tr>
<th>Index</th>
<th>Sink element</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>SAI5, left channel</td>
<td>Hardware sink</td>
</tr>
<tr>
<td>1</td>
<td>SAI5, right channel</td>
<td>Hardware sink</td>
</tr>
<tr>
<td>2</td>
<td>SAI3, left channel</td>
<td>Hardware sink</td>
</tr>
<tr>
<td>3</td>
<td>SAI3, right channel</td>
<td>Hardware sink</td>
</tr>
</tbody>
</table>
Table 7. Indexes of sink elements...continued

<table>
<thead>
<tr>
<th>Index</th>
<th>Sink element</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>AVTP, stream#0 left channel</td>
<td>AVB sink to network</td>
</tr>
<tr>
<td>5</td>
<td>AVTP, stream#0 right channel</td>
<td>AVB sink to network</td>
</tr>
<tr>
<td>6</td>
<td>AVTP, stream#1 left channel</td>
<td>AVB sink to network</td>
</tr>
<tr>
<td>7</td>
<td>AVTP, stream#1 right channel</td>
<td>AVB sink to network</td>
</tr>
</tbody>
</table>

As for the pipeline with Media Clock Recovery support:

![AVB Audio pipeline with Media Clock Recovery](image_url)

Table 8. Indexes of source elements

<table>
<thead>
<tr>
<th>Index</th>
<th>Source element</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Sine wave, 440 Hz</td>
<td>Software generated source</td>
</tr>
<tr>
<td>1</td>
<td>SAI3, left channel</td>
<td>Hardware source</td>
</tr>
<tr>
<td>2</td>
<td>SAI3, right channel</td>
<td>Hardware source</td>
</tr>
<tr>
<td>3</td>
<td>AVTP, stream#0 left channel</td>
<td>AVB source from network</td>
</tr>
<tr>
<td>4</td>
<td>AVTP, stream#0 right channel</td>
<td>AVB source from network</td>
</tr>
<tr>
<td>5</td>
<td>AVTP, stream#1 left channel</td>
<td>AVB source from network</td>
</tr>
<tr>
<td>6</td>
<td>AVTP, stream#1 right channel</td>
<td>AVB source from network</td>
</tr>
</tbody>
</table>

Table 9. Indexes of sink elements

<table>
<thead>
<tr>
<th>Index</th>
<th>Sink element</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>SAI3, left channel</td>
<td>Hardware sink</td>
</tr>
</tbody>
</table>
The sections below describe how to set up an (external) AVB Audio Media Server to enable the (Harpoon) AVB Listener and Talker.

### 4.4.4.4.1 AVB: Harpoon AVTP Listener

#### 4.4.4.4.1.1 AVB setup preparation

An i.MX 8M Plus EVK with Real-time Edge SW v2.5 (or above) can be used as a Talker. On the other end, any Harpoon supported EVK can be used as a Listener.

1. Connect the headphones/speakers to the HiFiBerry's RCA output or the Listener's audio Jack port.
2. Connect both the i.MX boards with an Ethernet RJ45 cable.
3. Connect a Serial/USB cable to each i.MX board and to some USB ports of the host PC.
4. Start consoles of the i.MX boards through the serial/USB ports.

<table>
<thead>
<tr>
<th>Index</th>
<th>Sink element</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SAI3, right channel</td>
<td>Hardware sink</td>
</tr>
<tr>
<td>2</td>
<td>AVTP, stream#0 left channel</td>
<td>AVB sink to network</td>
</tr>
<tr>
<td>3</td>
<td>AVTP, stream#0 right channel</td>
<td>AVB sink to network</td>
</tr>
<tr>
<td>4</td>
<td>AVTP, stream#1 left channel</td>
<td>AVB sink to network</td>
</tr>
<tr>
<td>5</td>
<td>AVTP, stream#1 right channel</td>
<td>AVB sink to network</td>
</tr>
</tbody>
</table>

AVB Talker (blue box) connected to the AVB Listener (orange box) through Ethernet.

**Figure 17. AVB Audio setup**
4.4.4.4.1.2 AVB Talker configuration (Linux)

The default AVB script needs to be modified to configure operations of the Talker entity as using a custom Media Application. The AVB Stack is provided with a simple Media Server application example, interfaced to the AVB stack through the GenAVB/TSN API, and supporting reading audio samples from a media file.

To enable AVB streaming using this media application, the endpoint needs to be configured as Endpoint AVB and the GenAVB/TSN configuration files needs to be modified as follows:

1. Power on the i.MX board and let the boot process complete
2. Configure the GenAVB/TSN stack to Endpoint AVB mode by setting GENAVB_TSN_CONFIG to the right value in the GenAVB/TSN mode configuration file:

   ```bash
   # vi /etc/genavb/config
   For i.MX 8M Plus EVK:
   GENAVB_TSN_CONFIG=2
   ```
3. Save and exit the file
4. Edit the GenAVB/TSN AVB configuration file using the following command:

   ```bash
   # vi /etc/genavb/config_avb
   ```
5. Set the configuration profile to PROFILE 2

   ```bash
   PROFILE=2
   ```
6. Save and exit the file.
7. A raw audio file `sample1_for_aaf.raw` is available in the `/home/media` repository. The multi-stream application example looks for audio files named `talker_mediaX.raw` in the `/home/media` repository, with X being the stream number. Therefore, before executing the multi-stream application, some symbolic links needs to be created in the `/home/media` directory for associating the `talker_mediaX.raw` names; here is an example for stream #0:

   ```bash
   # cd /home/media
   # ln -s sample1_for_aaf.raw talker_media0.raw
   ```
8. Enable the GenAVB/TSN systemd service to start the stack automatically on next reboot:

   ```bash
   # systemctl enable genavb-tsn
   ```
9. Reboot the board. The change is saved across reboots, so this has only to be done once.
10. Stop in U-Boot and select the AVB device tree blob before booting Linux:

    ```bash
    => setenv fdtfile imx8mp-evk-avb.dtb
    => boot
    ```

4.4.4.4.1.3 AVB Listener configuration (Harpoon)

The AVB Listener is implemented in Harpoon interfaces with the AVB stack through the GenAVB/TSN API, and supports reading audio samples from the network while pushing out the audio data - through the audio pipeline - on the SAI interfaces.

The below steps must be executed to enable the AVB Listener on Harpoon side:

1. Power on the i.MX board and stop the boot process in U-Boot to fetch the AVB DTB file:

   ```bash
   => setenv jh_root_dtb imx8mp-evk-avb.dtb
   => run jh_mmcboot
   ```
2. Start the FreeRTOS audio application using the following command at the Linux prompt:

```
# harpoon_set_configuration.sh freertos avb
# systemctl start harpoon
```

3. Start the AVB pipeline, connecting the AVTP source element (stream #0) to the SAI output (e.g.: HiFiBerry board)

```
# harpoon_ctrl audio -r 4
# harpoon_ctrl routing -i 5 -o 0 -c
# harpoon_ctrl routing -i 6 -o 1 -c
```

4. Watch for AVTP source logs once the stream is connected (see next section):

```
INFO: avtp_source_element_st: rx stream: 0, avtp(C067ABF0, 0)
INFO: avtp_source_element_st: connected: 1
INFO: avtp_source_element_st: batch size: 64
INFO: avtp_source_element_st: underflow: 459, overflow: 0 err: 0 received: 208617
INFO: avtp_source_element_st: rx stream: 1, avtp(0, 0)
INFO: avtp_source_element_st: connected: 0
INFO: avtp_source_element_st: batch size: 0
INFO: avtp_source_element_st: underflow: 0, overflow: 0 err: 0 received: 0
```

4.4.4.4.1.4 AVB Listener with Media clock Recovery configuration (Harpoon)

The media clock recovery feature permits the listener to synchronize its media clock to a remote master clock through gPTP timestamps in the AVTP stream. On boards that support this feature, we can enable the Harpoon AVB listener to use timestamps from the AVTP stream to tune its own audio PLL and prevent audio clock drifts with the AVB talker. This feature is only available on i.MX8MP EVK for now and SAI3 output only.

The below steps must be executed to enable the AVB Listener (with MCR support) on Harpoon side:

1. Power on the i.MX board and stop the boot process in U-Boot to fetch the AVB DTB file:

```
=> setenv jh_root_dtb imx8mp-evk-harpoon-avb.dtb
=> run jh_mmcboot
```

2. Start the FreeRTOS audio application using the following command at the Linux prompt:

```
# harpoon_set_configuration.sh freertos avb
# systemctl start harpoon
```

3. Start the AVB pipeline, connecting the AVTP source element (stream #0) to the SAI output (e.g.: on board jack)

```
# harpoon_ctrl audio -r 6
# harpoon_ctrl routing -i 3 -o 0 -c
# harpoon_ctrl routing -i 4 -o 1 -c
```

4. Watch for AVTP source logs once the stream is connected (see next section):

```
INFO: avtp_source_element_st: rx stream: 0, avtp(C067ABF0, 0)
INFO: avtp_source_element_st: connected: 1
INFO: avtp_source_element_st: batch size: 64
INFO: avtp_source_element_st: underflow: 459, overflow: 0 err: 0 received: 208617
INFO: avtp_source_element_st: rx stream: 1, avtp(0, 0)
INFO: avtp_source_element_st: connected: 0
INFO: avtp_source_element_st: batch size: 0
INFO: avtp_source_element_st: underflow: 0, overflow: 0 err: 0 received: 0
```

You can also see logs about the Media Clock Recovery execution:

```
INFO  23.157693775 os   mclock_rec_pll_stats : adjust  = 0
```
4.4.4.4.15 AVB stream connection

This section describes how to use AVDECC events to configure the stream output of the Talker to the input of the Listener. To do so, we may use the GenAVB AVDECC controller application available on the Talker endpoint:

```
# genavb-controller-app -h
NXP's GenAVB AVDECC controller demo application

Usage:
app [options]

Options:
-S <control_type> <entity_id> <control_index> <value>
   Set a given control to the given value where control_type must be uint8 or utf8 (For utf8: <value> must be string of max 99 characters)
-G <control_type> <entity_id> <control_index>
   Get a control value where control_type must be uint8 or utf8
-l
   list discovered AVDECC entities
-c <talker_entity_id> <talker_unique_id> <listener_entity_id> <listener_unique_id> <flags>
   connect a stream between a talker and a listener
-d <talker_entity_id> <talker_unique_id> <listener_entity_id> <listener_unique_id> <flags>
   disconnect a stream between a talker and a listener
-r <listener_entity_id> <listener_unique_id>
   Get information about a listener sink
-t <talker_entity_id> <talker_unique_id>
   Get information about a talker source
-s <talker_entity_id> <talker_unique_id> <index>
   Get information from a talker about a given connection/stream
-T <talker_entity_id> <talker_unique_id> <start|stop>
   Send START_STREAMING or STOP_STREAMING command to a talker
-L <listener_entity_id> <listener_unique_id> <start|stop>
   Send START_STREAMING or STOP_STREAMING command to a listener
-h
   print this help text
```

First of all, the Talker's entity information can be displayed by using the AVDECC controller application (available on the talker endpoint):

```
# genavb-controller-app -l
NXP's GenAVB AVDECC controller demo application

Number of discovered entities: 2
Entity ID = 0x49F070F840001 Model ID = 0x49F000080001
capabilities = 0x8 Association ID = 0x0 MAC address= 00:04:9F:07:0F:84 Local MAC address= 00:04:9F:07:0F:84
Controller
Controls:
None
```
To disconnect a stream, use the command:

```
# genavb-controller-app -d <talker_entity_id> <talker_unique_id> <listener_entity_id>
```

To connect streams, use the following command:

```
# genavb-controller-app -c <talker_entity_id> <talker_unique_id> <listener_entity_id>
```

Once the Listener is running, its entity ID can be displayed by using the same tool:

```
# genavb-controller-app -d <talker_entity_id> <talker_unique_id> <listener_entity_id>
```
In the below example, the Listener’s stream #0 is connected to the Talker’s stream #0:

```
$ genavb-controller-app -c 0x49f070f840000 0 0x49fddee100000 0 0
NXP's GenAVB AVDECC controller demo application
Stream connection successful: stream id = 0x49f070f840000 Destination MAC address 91:E0:F0:00:FE:24
flags = 0x0 connection_count = 1 VLAN id = 0
```

Once the stream is connected, the audio file can be heard on the SAI output lines.

4.4.4.4.2 AVB: Harpoon AVTP Talker

4.4.4.4.2.1 AVB setup preparation

An i.MX 8M Plus EVK with Real-time Edge SW v2.5 (or above) can be used as a Listener. On the other end, any Harpoon supported EVK can be used as a Talker.

1. Connect the headphones/speakers to the Listener’s audio Jack port.
2. Connect both the i.MX boards with an Ethernet RJ45 cable.
3. Connect a Serial/USB cable to each i.MX board and to some USB ports of the host PC.
4. Start consoles of the i.MX boards through the serial/USB ports.

AVB Talker (blue box) connected to the AVB Listener (orange box) through Ethernet.

![Figure 18. AVB Audio setup](image)

4.4.4.4.2.2 AVB Listener configuration (Linux)

The default AVB configuration needs to be modified to enable the Listener entity in a custom Media Application. The AVB Stack is provided with a simple Media Server application example, interfaced to the AVB stack through the GenAVB/TSN API.
To enable AVB listening using this media application, the endpoint needs to be configured as Endpoint AVB and the GenAVB/TSN configuration files needs to be modified as follows:

1. Power on the i.MX board and let the boot process complete
2. Configure the GenAVB/TSN stack to Endpoint AVB mode by setting GENAVB_TSN_CONFIG to the right value in the GenAVB/TSN mode configuration file:
   ```bash
   # vi /etc/genavb/config
   GENAVB_TSN_CONFIG=2
   ```
3. Save and exit the file
4. Edit the GenAVB/TSN AVB configuration file using the following command:
   ```bash
   # vi /etc/genavb/config_avb
   PROFILE=14
   ```
5. Save and exit the file.
6. Enable the GenAVB/TSN systemd service to start the stack automatically on next reboot:
   ```bash
   # systemctl enable genavb-tsn
   ```
7. Reboot the board. The change is saved across reboots, so this has only to be done once.

---

4.4.4.4.2.3 AVB Talker configuration (Harpoon)

The AVB Talker implemented in Harpoon interfaces with the AVB stack through the GenAVB/TSN API, and supports audio streaming to the network while reading the audio data - through the audio pipeline - from the SAI interfaces.

The below steps must be executed to enable the AVB Talker on Harpoon side:

1. Power on the i.MX board and stop the boot process in U-Boot to fetch the AVB DTB file:
   ```bash
   => setenv jh_root_dtb imx8mp-evk-harpoon-avb.dtb
   => run jh_mmcboot
   ```
2. Start the FreeRTOS audio application using the following command at the Linux prompt:
   ```bash
   # harpoon_set_configuration.sh freertos avb
   # systemctl start harpoon
   ```
3. Start the AVB pipeline, connecting the SAI input (e.g.: HifiBerry board) to the AVTP sink element (stream #0)
   ```bash
   # harpoon_ctrl audio -r 4 -a 00:bb:cc:dd:be:ef
   # harpoon_ctrl routing -i 1 -o 4 -c
   # harpoon_ctrl routing -i 2 -o 5 -c
   ```
4. Watch for AVTP sink logs once the stream is connected (see next section):
   ```plaintext
   INFO: avtp_sink_element_st: rx stream: 0, avtp(C067ABF0, 0)
   INFO: avtp_sink_element_st: connected: 1
   INFO: avtp_sink_element_st: batch size: 64
   ```
4.4.4.2.4 AVB stream connection

This section describes how to use AVDECC events to configure the stream output of the Talker to the input of the Listener. To do so, we may use the GenAVB AVDECC controller application available on the Listener (Linux endpoint):

```bash
# genavb-controller-app -h
NXP's GenAVB AVDECC controller demo application

Usage:
app [options]

Options:
-S <control_type> <entity_id> <control_index> <value>   Set a given control to the given value where control_type must be uint8 or utf8 (For utf8: <value> must be string of max 99 characters)
-G <control_type> <entity_id> <control_index>           Get a control value where control_type must be uint8 or utf8
-l                                                      list discovered AVDECC entities
-d <talker_entity_id> <talker_unique_id> <listener_entity_id> <listener_unique_id> <flags>   connect a stream between a talker and a listener
-s <talker_entity_id> <talker_unique_id> <index>        Get information from a talker about a given connection/stream
-r <listener_entity_id> <listener_unique_id>            Get information about a listener sink
-t <talker_entity_id> <talker_unique_id>                Get information about a talker source
-T <talker_entity_id> <talker_unique_id> <start|stop>           Send START_STREAMING or STOP_STREAMING command to a talker
-L <listener_entity_id> <listener_unique_id> <start|stop>       Send START_STREAMING or STOP_STREAMING command to a listener
-h                                                              print this help text
```

First of all, the Talker's entity information can be displayed by using the AVDECC controller application (available on the talker endpoint):

```bash
# genavb-controller-app -l
NXP's GenAVB AVDECC controller demo application
Number of discovered entities: 4
Entity ID = 0x49f05cf720001   Model ID = 0x49f00000080001   Capabilities = 0x8 Association ID = 0x0   MAC address= 00:04:9F:05:CF:72   Local MAC address= 00:04:9F:05:CF:72
  Controller
  Controls:
    None

Entity ID = 0x49f0700000001   Model ID = 0x49f00000090001   Capabilities = 0x708 Association ID = 0x0   MAC address= 00:04:9F:07:00:84   Local MAC address= 00:04:9F:05:CF:72
  Talker:
    sources = 8   capabilities = 0x4001
    Stream 0: name = Stream output 0   interface index = 0   number of formats = 1
      flags = Ox6   current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
    Stream 1: name = Stream output 1   interface index = 0   number of formats = 1
      flags = Ox6   current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
    Stream 2: name = Stream output 2   interface index = 0   number of formats = 1
      flags = Ox6   current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
    Stream 3: name = Stream output 3   interface index = 0   number of formats = 1
      flags = Ox6   current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
    Stream 4: name = Stream output 4   interface index = 0   number of formats = 1
      flags = Ox6   current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
    Stream 5: name = Stream output 5   interface index = 0   number of formats = 1
      flags = Ox6   current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
```
To connect streams, use the following command:

```bash
# genavb-controller-app -c <talker_entity_id> <talker_unique_id> <listener_entity_id> <flag>
```

Once the Talker is running, its entity ID can be displayed by using the same tool:

```plaintext
Entity ID = 0x49fddbeef0000    Model ID = 0x49fff00000001    Capabilities = 0x708    Association ID = 0x0   MAC address= 00:BB:CC:DD:BE:EF   Local MAC address= 00:04:9F:05:CF:72
Talker:    sources = 3    capabilities = 0x4801
Stream:     name =      Stream output 0    interface index = 0    number of formats = 1
flags = 0x6    current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
Stream:     name =      Stream output 1    interface index = 0    number of formats = 1
flags = 0x6    current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
Stream:     name =      Stream output 2    interface index = 0    number of formats = 1
flags = 0x6    current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
Stream:     name =      Stream output 3    interface index = 0    number of formats = 1
flags = 0x6    current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
Stream:     name =      Stream output 4    interface index = 0    number of formats = 1
flags = 0x6    current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
Stream:     name =      Stream output 5    interface index = 0    number of formats = 1
flags = 0x6    current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
Stream:     name =      Stream output 6    interface index = 0    number of formats = 1
flags = 0x6    current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
Stream:     name =      Stream output 7    interface index = 0    number of formats = 1
flags = 0x6    current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
Controls:    Control 0: name = Volume Control 0    type = 0x90e0f00000000004    read-only = No
value_type = 1    min = 0    current = 100    max = 100    step = 1
```

To connect streams, use the following command:

```bash
# genavb-controller-app -c <talker_entity_id> <talker_unique_id> <listener_entity_id> <flag>
```
To disconnect a stream, use the command:

```
# genavb-controller-app -d <talker_entity_id> <talker_unique_id> <listener_entity_id> <listener_unique_id>
```

In the below example, the Listener's stream #0 is connected to the Talker's stream #0:

```
# genavb-controller-app -c 0x49fddbeef0000 0 0x49f070f840000 0 0
NXP's GenAVB AVDECC controller demo application
Stream connection successful: stream id = 0xbbccddbeef0000 Destination MAC address
91:E0:F0:00:FE:21 flags = 0x0 connection_count = 1 VLAN id = 0
```

Once the stream is connected, the audio file can be heard on the SAI output lines.

### 4.4.4.4.3 AVB Connect Harpoon Listeners and Talker through an AVB bridge

#### 4.4.4.4.3.1 AVB setup preparation

The AVB Listeners and Talker implemented in Harpoon can be connected with each other, and support reading audio samples from the network while pushing out the audio data - through the audio pipeline - on the SAI interfaces.

- Two or more AVB endpoints (i.MX 8M Plus EVK, i.MX 8M Mini EVK, or i.MX 8M Nano EVK)
- AVDECC controller (e.g., i.MX 8M Plus EVK with Real-time Edge SW v2.6 as AVB endpoint using `genavb-controller-app`)
- One AVB bridge (e.g., LS1028ARDB with Real-time Edge SW v2.6)

![Figure 19. Harpoon AVTP Talker/Listener setup](image)
4.4.4.4.3.2 AVB Bridge Configuration

Use the following commands to configure bridge on LS1028ARDB:

```
# avb-bridge.sh
# avb.sh start
```

4.4.4.4.3.3 AVB Listeners configuration (Harpoon)

The AVB Listener is implemented in Harpoon interfaces with the AVB stack through the GenAVB/TSN API, and supports reading audio samples from the network while pushing out the audio data - through the audio pipeline - on the SAI interfaces.

The below steps must be executed to enable the AVB Listener on Harpoon side:

1. Power on the i.MX board and stop the boot process in U-Boot to fetch the AVB DTB file:
   ```
   => setenv jh_root_dtb imx8mp-evk-harpoon-avb.dtb
   => run jh_mmcboot
   ```

2. Start the FreeRTOS audio application using the following command at the Linux prompt:
   ```
   # harpoon_set_configuration.sh freertos avb
   # systemctl start harpoon
   ```

3. Start the AVB pipeline, connecting the AVTP source element (stream #0) to the SAI output (e.g.: HiFiBerry board)
   ```
   # harpoon_ctrl audio -r 4 -a 00:bb:cc:dd:be:ef
   # harpoon_ctrl routing -i 5 -o 0 -c
   # harpoon_ctrl routing -i 6 -o 1 -c
   ```

4. For other AVB AVTP Listener instances, use a different MAC address:
   ```
   # harpoon_ctrl audio -r 4 -a 00:bb:cc:dd:ca:fe
   # harpoon_ctrl routing -i 5 -o 0 -c
   # harpoon_ctrl routing -i 6 -o 1 -c
   ```

5. Watch for AVTP source logs once the stream is connected (see next section):
   ```
   INFO: avtp_source_element_st: rx stream: 0, avtp(C067ABF0, 0)
   INFO: avtp_source_element_st: connected: 1
   INFO: avtp_source_element_st: batch size: 64
   INFO: avtp_source_element_st: underflow: 459, overflow: 0 err: 0 received: 208617
   INFO: avtp_source_element_st: rx stream: 1, avtp(0, 0)
   INFO: avtp_source_element_st: connected: 0
   INFO: avtp_source_element_st: batch size: 0
   INFO: avtp_source_element_st: underflow: 0, overflow: 0 err: 0 received: 0
   ```

4.4.4.4.3.4 AVB Talker configuration (Harpoon)

The AVB Talker implemented in Harpoon interfaces with the AVB stack through the GenAVB/TSN API, and supports audio streaming to the network while reading the audio data - through the audio pipeline - from the SAI interfaces.

The below steps must be executed to enable the AVB Talker on Harpoon side:

1. Power on the i.MX board and stop the boot process in U-Boot to fetch the AVB DTB file:
   ```
   => setenv jh_root_dtb imx8mp-evk-harpoon-avb.dtb
   => run jh_mmcboot
   ```
2. Start the FreeRTOS audio application using the following command at the Linux prompt:

```
# harpoon_set_configuration.sh freertos avb
# systemctl start harpoon
```

3. Start the AVB pipeline, connecting the SAI input (e.g.: HiFiBerry board) to the AVTP sink element (stream #0)

```
# harpoon_ctrl audio -r 4 -a 00:bb:cc:dd:de:ad
# harpoon_ctrl routing -i 1 -o 4 -c
# harpoon_ctrl routing -i 2 -o 5 -c
```

4. Watch for AVTP sink logs once the stream is connected (see next section):

```
INFO: avtp_sink_element_st: rx stream: 0, avtp(C067ABF0, 0)
INFO: avtp_sink_element_st: connected: 1
INFO: avtp_sink_element_st: batch size: 64
INFO: avtp_sink_element_st: underflow: 459, overflow: 0 err: 0 sent: 208617
INFO: avtp_sink_element_st: rx stream: 1, avtp(0, 0)
INFO: avtp_sink_element_st: connected: 0
INFO: avtp_sink_element_st: batch size: 0
INFO: avtp_sink_element_st: underflow: 0, overflow: 0 err: 0 sent: 0
```

### 4.4.4.4.3.5 AVDECC controller configuration (Linux)

To enable the usage the command line AVB AVDECC controller, the AVB stack needs to be started as Endpoint AVB. For that, the GenAVB/TSN configuration files needs to be modified as follows:

1. Power on the i.MX board and let the boot process complete
2. Configure the GenAVB/TSN stack to Endpoint AVB mode by setting GENAVB_TSN_CONFIG to the right value in the GenAVB/TSN mode configuration file:

   ```
   # vi /etc/genavb/config
   ```

   - For i.MX 8M Plus EVK:
     ```
     GENAVB_TSN_CONFIG=2
     ```
   - For i.MX 8M Mini EVK:
     ```
     GENAVB_TSN_CONFIG=1
     ```

3. Save and exit the file
4. Enable the GenAVB/TSN systemd service to start the stack automatically on next reboot:

   ```
   # systemctl enable genavb-tsn
   ```

5. Reboot the board. The change is saved across reboots, so this has only to be done once.
6. Stop in U-Boot and select the AVB device tree blob before booting Linux:

   - For i.MX 8M Plus EVK:
     ```
     => setenv fdtfile imx8mp-evk-avb.dtb
     => boot
     ```
   - For i.MX 8M Mini EVK:
     ```
     => setenv fdtfile imx8mm-evk-avb.dtb
     => boot
     ```
4.4.4.3.6 AVB stream connection

This section describes how to use AVDECC events to connect the stream output of the Talker to the stream inputs of the Listeners. To do so, we may use the GenAVB AVDECC controller previously configured:

```
# genavb-controller-app -h
NXP's GenAVB AVDECC controller demo application
Usage:
  app [options]
Options:
  -S <control_type> <entity_id> <control_index> <value>  Set a given control to the given
    value where control_type
    must be uint8 or utf8 (For utf8:
    <value> must be string of max 99 characters)
  -G <control_type> <entity_id> <control_index>           Get a control value where
    control_type must be uint8 or utf8
  -l                                                      list discovered AVDECC entities
  -d <talker_entity_id> <talker_unique_id> <listener_entity_id> <listener_unique_id>
    connect a stream between a talker and a listener
  -r <listener_entity_id> <listener_unique_id>            Get information about a listener
    sink
  -t <talker_entity_id> <talker_unique_id>                Get information about a talker
    source
  -a <talker_entity_id> <talker_unique_id> <index>        Get information from a talker about
    a given connection/stream
  -T <talker_entity_id> <talker_unique_id> <start|stop>           Send START_STREAMING or
    STOP_STREAMING command to a talker
  -L <listener_entity_id> <listener_unique_id> <start|stop>       Send START_STREAMING or
    STOP_STREAMING command to a listener
  -h                                                              print this help text
```

First of all, the Talker's entity information can be displayed by using the AVDECC controller application:

```
# genavb-controller-app -l
NXP's GenAVB AVDECC controller demo application
Number of discovered entities: 4
Entity ID = 0x49f05cf720001  Model ID = 0x49f0000080001  Capabilities = 0x8 Association ID =
0x0  MAC address= 00:04:9F:05:CF:72  Local MAC address= 00:04:9F:05:CF:72
Talker:     sources = 8     capabilities = 0x4801
  Stream 0: name =      Stream output 0    interface index = 0    number of formats = 1
    flags = 0x6 current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
  Stream 1: name =      Stream output 1    interface index = 0    number of formats = 1
    flags = 0x6 current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
  Stream 2: name =      Stream output 2    interface index = 0    number of formats = 1
    flags = 0x6 current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
  Stream 3: name =      Stream output 3    interface index = 0    number of formats = 1
    flags = 0x6 current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
  Stream 4: name =      Stream output 4    interface index = 0    number of formats = 1
    flags = 0x6 current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
  Stream 5: name =      Stream output 5    interface index = 0    number of formats = 1
    flags = 0x6 current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
  Stream 6: name =      Stream output 6    interface index = 0    number of formats = 1
    flags = 0x6 current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
  Stream 7: name =      Stream output 7    interface index = 0    number of formats = 1
    flags = 0x6 current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
Listener:   sinks = 8     capabilities = 0x4801
  Stream 0: name =      Stream input 0    interface index = 0    number of formats = 1
    flags = 0x6 current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
  Stream 1: name =      Stream input 1    interface index = 0    number of formats = 1
    flags = 0x6 current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
  Stream 2: name =      Stream input 2    interface index = 0    number of formats = 1
    flags = 0x6 current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
  Stream 3: name =      Stream input 3    interface index = 0    number of formats = 1
    flags = 0x6 current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
  Stream 4: name =      Stream input 4    interface index = 0    number of formats = 1
    flags = 0x6 current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
  Stream 5: name =      Stream input 5    interface index = 0    number of formats = 1
    flags = 0x6 current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
  Stream 6: name =      Stream input 6    interface index = 0    number of formats = 1
    flags = 0x6 current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
  Stream 7: name =      Stream input 7    interface index = 0    number of formats = 1
    flags = 0x6 current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
```
Stream 3: name = Stream input 3  interface index = 0  number of formats = 1
flags = 0x6  current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
Stream 4: name = Stream input 4  interface index = 0  number of formats = 1
flags = 0x6  current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
Stream 5: name = Stream input 5  interface index = 0  number of formats = 1
flags = 0x6  current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
Stream 6: name = Stream input 6  interface index = 0  number of formats = 1
flags = 0x6  current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
Stream 7: name = Stream input 7  interface index = 0  number of formats = 1
flags = 0x6  current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
Controls:
Control 0: name = Volume Control 0  type = 0x90e0f0000000004  read-only = No
value_type = 1  min = 0  current = 100  max = 100  step = 1

Stream 0: name = Stream output 0  interface index = 0  number of formats = 1
flags = 0x6  current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
Stream 1: name = Stream output 1  interface index = 0  number of formats = 1
flags = 0x6  current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
Stream 2: name = Stream output 2  interface index = 0  number of formats = 1
flags = 0x6  current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )

Controls:
Control 0: name = Volume Control 0  type = 0x90e0f0000000004  read-only = No
value_type = 1  min = 0  current = 100  max = 100  step = 1

Once the Talker is running, its entity ID can be displayed by using the same tool:

Entity ID = 0x49fdddead0000  Model ID = 0x49fddbeef00000  Capabilities = 0x708  Association ID = 0x0
MAC address= 00:BB:CC:DD:BE:EF  Local MAC address= 00:04:9F:05:CF:72
Talker:  sources = 3  capabilities = 0x4801
Stream 0: name = Stream output 0  interface index = 0  number of formats = 1
flags = 0x6  current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
Stream 1: name = Stream output 1  interface index = 0  number of formats = 1
flags = 0x6  current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
Stream 2: name = Stream output 2  interface index = 0  number of formats = 1
flags = 0x6  current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
Listener:  sinks = 3  capabilities = 0x4801
Stream 0: name = Stream input 0  interface index = 0  number of formats = 1
flags = 0x6  current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
Stream 1: name = Stream input 1  interface index = 0  number of formats = 1
flags = 0x6  current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )
Stream 2: name = Stream input 2  interface index = 0  number of formats = 1
flags = 0x6  current_format = 0x0205021800806000 ( AAF 2chans 24/32bits 48000Hz 6samples/packet )

Controls:
Control 0: name = Volume Control 0  type = 0x90e0f0000000004  read-only = No
value_type = 1  min = 0  current = 100  max = 100  step = 1

To connect streams, use the following command:

$ genavb-controller-app -c <talker_entity_id> <talker_unique_id> <listener_entity_id> <listener_unique_id>

To disconnect a stream, use the command:

$ genavb-controller-app -d <talker_entity_id> <talker_unique_id> <listener_entity_id>

In the below example, the Listener's stream #0 is connected to the Talker's stream #0:

$ genavb-controller-app -c 0x49fdddead0000 0x49fddbeef0000 0 0
NXP's GenAVB AVDECC controller demo application
Once the stream is connected, the audio file can be heard on the SAI output lines.

4.4.4.5 Playing an SMP full audio pipeline

The use case for SMP audio pipeline is only supported on Zephyr which runs SMP kernel on two CPU Cores, it will create and bind one dedicated data thread for each CPU Core.

The main motivation for SMP support is to distribute the CPU load of the pipeline processing across available cores, and thus be able to run pipelines that consume more than one single core CPU resources.

The main approach used is to split existing pipelines in two pieces, and process them, asynchronously, in different cores/data threads. This allows the two pieces to fully run in parallel, but usually requires a one period increase in the end to end latency. For example:

- Before: 1 audio pipeline, running in one core/data thread. Processing period P, with an end to end latency of 2 x P.
- After: Pipeline is split into two 2 pipelines. Each runs on a separate core. Explicit synchronization between the two threads/pipelines is avoided, by adding an extra buffer of P length between the two pipelines. Processing period is still P, but end to end latency is now 3 x P.

This basically models one pipeline as two independent ones:

- The first one has no sink elements, it terminates with output buffers
- The second one has a specific source element, that implements the extra buffer between pipelines.
- The scheduling of all the thread handling is done based on the same IRQ.

This approach can also be scaled to more CPUs, each time splitting the pipeline into several pieces, each new thread/piece increasing the end to end latency by P.

The reference audio application is splitting the pipeline used by “full audio pipeline” use case into two audio data pipelines, each pipeline runs on a dedicated thread binded to a dedicated CPU Core.
To run the Zephyr audio SMP pipeline application, the following command can be run to generate an appropriate configuration file:

```bash
# harpoon_set_configuration.sh zephyr audio_smp
```

**Note:** Avoid changing the configuration while the Harpoon service is running (silent failure when restarting the service).

And run the harpoon service with systemctl in order to start Jailhouse.

```bash
# systemctl start harpoon
```

Then use the following command to run audio SMP pipeline testcase:

```bash
# harpoon_ctrl audio -r 5
```

You can then connect the provided sources to audio outputs:

```bash
# harpoon_ctrl routing -i 4 -o 2 -c # SAI5's input to SAI3's output (L)
# harpoon_ctrl routing -i 5 -o 3 -c # SAI5's input to SAI3's output (R)
```

To run another audio use case, the playback must be stopped with the following command:

```bash
# harpoon_ctrl audio -s
```

### 4.5 Industrial application
4.5.1 Features of the industrial application

The industrial application is available in the Harpoon share directory of the root file system:

<table>
<thead>
<tr>
<th>Directory</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>/usr/share/harpoon/inmates/freertos/industrial.bin</td>
<td>FreeRTOS binary</td>
</tr>
<tr>
<td>/usr/share/harpoon/inmates/zephyr/industrial.bin</td>
<td>Zephyr binary</td>
</tr>
</tbody>
</table>

The different use cases are:

- **FlexCAN-based communication (only on i.MX 8M Plus EVK):**
  - Two boards (nodes) are connected through their CAN bus connectors (J19) using a male-to-male DB9 CAN bus cable. The latter can either be purchased or built following the CAN pinout standard.
  - Each node is configured to handle multiple message buffers. Where a message buffer is either configured for transmit or receive.
  - Both nodes send/receive either CAN or CAN FD messages.

- **Ethernet:**
  - Simple MCUXpresso SDK API based application to send and receive packets through the ENET interface:
    - ENET application for FreeRTOS and Zephyr on i.MX 8M Mini/Nano EVK
    - ENET_QoS application with or without internal loopback for Zephyr on i.MX 8M Plus EVK
  - Full TSN stack based application, running a gPTP stack and sending/receiving TSN packets on a TSN network:
    - Through the ENET_QOS interface, acting as a controller/IO device (i.MX 8M Plus EVK).
    - Through the ENET interface, acting as a controller/IO device (i.MX 8M Mini EVK and i.MX 8M Nano EVK).
  
  **Note:** The ENET interface does not support 802.1Qbv. Packets are transmitted using basic, software based, strict priority scheduling.

4.5.2 Starting the industrial application

To use the industrial application, Jailhouse must be started first. To start Jailhouse and the industrial application, create the corresponding Harpoon configuration file and run the harpoon service using `systemd`, for example:

```
# harpoon_set_configuration.sh freertos industrial
```

The configuration file is stored under `/etc/harpoon/harpoon.conf` and the Harpoon systemd service uses it to start Jailhouse and the industrial application:

```
# systemctl start harpoon
```

Once the Harpoon service has been started, `harpoon_ctrl` is used to start or stop the industrial features with optional parameters. The different options for the industrial application are as follows:

**Industrial FlexCAN options:**
- `-r <id>` run CAN mode id:
  - 0 - Multiple Nodes and Messages Tx+Rx
- `-n <node_type>` acting as node 'A' or 'B' (default 'A')
  - 0 - node 'A'
  - 1 - node 'B'
- `-o <protocol>` use 'CAN' or 'CAN FD' protocol (default 'CAN')
  - 0 - protocol is 'CAN'
  - 1 - protocol is 'CAN FD'
- `-s` stop FlexCAN based communication

**Industrial ethernet options:**
**4.5.3 Running the industrial application: examples**

**4.5.3.1 FlexCAN multiple nodes communication**

**4.5.3.1.1 Industrial CAN application overview**

The industrial CAN application is configured to perform communication between two nodes. Each node has four message buffers used equally for transmit and receive (two MBs for transmit and two MBs for receive). The transmission is driven by a periodic timer (currently configured at 1200 us) and reception is done on frame reception.

![Industrial CAN application architecture](image)

**4.5.3.1.2 FlexCAN multiple nodes use case**

To start the FlexCAN based communication:

- One board needs to be selected as Node A \(-n 0\) and the other as Node B \(-n 1\).
- Select the same CAN protocol on both nodes: \(-o 0\) for CAN and \(-o 1\) for CAN FD. Default is CAN protocol.

On board A, start CAN protocol multiple node use case as Node A:

```
# harpoon_ctrl can -r 0 -n 0
```
On board B, start CAN protocol multiple node use case as Node B:

\[ \# \text{harpoon_ctrl can -r 0 -n 1} \]

Type this command to stop the current use case (mandatory before starting a new use case):

\[ \# \text{harpoon_ctrl can -s} \]

During the execution of the application, reception and transmission are dumped on console every 10 seconds:

- TX and RX interruptions irq:
  - A TX interruption is triggered when the application manages to send a message to the receiver.
  - An RX interruption is triggered when a message is received.
- Reads and writes in the message buffer memory tx and rx.
- Read/write failures fail: It occurs when the application fails to read or write into message buffer memory.
- TX busy operations busy: It occurs when the application is not able to write another frame because it is still waiting for the TX interruption from the previous one (This can also happen when the receiver is not in run mode or not configured properly).
- RX overflows ovrflw: It occurs when the message buffer is busy and cannot receive the new frame.
- Global interrupts number global irq: A global interruption may signal both RX and TX interruptions at the same time. It is possible that the global IRQ number is lower than the total TX and RX interruptions.

Industrial CAN application logs example:

- **Node A:**

  INFO: can_stats : |Mbit/s: 2|TX period µs: 1200|global irq: 5532306|
  INFO: can_stats : |TX mb: 1, id: 123|-->|irq: 1383079|tx: 1383079|busy : 2350|fail: 0|
  INFO: can_stats : |RX mb: 2, id: 321|-->|irq: 1383074|rx: 1383074|ovrflw: 0|fail: 0|
  INFO: can_stats : |TX mb: 3, id: 124|-->|irq: 1383079|tx: 1383079|busy : 2350|fail: 0|
  INFO: can_stats : |RX mb: 4, id: 422|-->|irq: 1383074|rx: 1383074|ovrflw: 0|fail: 0|

- **Node B:**

  INFO: can_stats : |Mbit/s: 2|TX period µs: 1200|global irq: 5544926|
  INFO: can_stats : |TX mb: 1, id: 321|-->|irq: 1389384|tx: 1389384|busy : 0|fail: 0|
  INFO: can_stats : |RX mb: 2, id: 123|-->|irq: 1383079|rx: 1383079|ovrflw: 0|fail: 0|
  INFO: can_stats : |TX mb: 3, id: 422|-->|irq: 1389384|tx: 1389384|busy : 0|fail: 0|

In the example above, the timer period is 1200 us and the baudrate of the CAN bus is 2 Mbits/s for CAN FD (1 Mbits/s for CAN).

### 4.5.3.2 Ethernet through MCUXpresso SDK API

A simple reference use case is given to exchange Ethernet packets using the SDK API.

1. Run the ENET test case on i.MX 8M Mini/Nano EVK.

   harpoon_ctrl ethernet -r 1

One possibility to verify that the use case is functional is to plug an Ethernet cable on the Ethernet connector on one end, and to a Linux host computer on the other end. The expected output on the inmate cell console is as follows:

```
ENET test start.
ENET: Wait for PHY link up...
ENET: PHY link speed 1000M full-duplex
INFO: ethernet_sdk_enet_stat: not implemented
INFO: cpu_load_stats : CPU load: 0.00%
ENET test result:
```

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To verify that data are successfully received on the host side, one may use the `tcpdump` tool (sudo permissions may be required):

```
$ tcpdump -i <INTERFACE> -e
```

tcpdump: verbose output suppressed, use -v or -vv for full protocol decode
listening on enp1s2, link-type EN10MB (Ethernet), capture size 262144 bytes
11:48:40.402104 00:04:9f:06:96:36 (oui Freescale) > 01:80:c2:00:00:0e (oui Unknown), ethtype LLDP (0x88cc), length 269: LLDP, length 255: imx8mp-lpddr4-evk
11:48:46.648227 00:00:00:00:00:00 (oui Ethernet) > Broadcast, 802.3, length 986: LLC, dsap Null (0x00) Individual, ssap Null (0x00) Response, ctrl 0x0302: Information, send seq 1, rcv seq 1, Flags [Final], length 986
0x0000: 0001 0203 0405 0607 0809 0a0b 0c0d 0e0f 0102 0304 0506 0708 090a 0b0c 0d0e 0f10 0123 0405 0607 0809 0a0b 0c0d 0e0f 0102 0304 0506 0708 090a 0b0c 0d0e 0f10 0123 0405 0607 0809 0a0b 0c0d 0e0f 0102 0304 0506 0708 090a 0b0c 0d0e 0f10 0123 0405 0607 0809 0a0b 0c0d 0e0f 0102 0304 0506 0708 090a 0b0c 0d0e 0f10 0123 0405 0607 0809 0a0b 0c0d 0e0f 0102 0304 0506 0708 090a 0b0c 0d0e 0f10 0123 0405 0607 0809 0a0b 0c0d 0e0f 0102 0304 0506 0708 090a 0b0c 0d0e 0f10 0123 0405 0607 0809 0a0b 0c0d 0e0f 0102 0304 0506 0708 090a 0b0c 0d0e 0f10 0123 0405 0607 0809 0a0b 0c0d 0e0f 0102 0304 0506 0708 090a 0b0c 0d0e 0f10 0123 0405 0607 0809 0a0b 0c0d 0e0f 0102 0304 0506 0708 090a 0b0c 0d0e 0f10 0123 0405 0607 0809 0a0b 0c0d 0e0f 0102 0304 0506 0708 090a 0b0c 0d0e 0f10 0123 0405 0607 0809 0a0b 0c0d 0e0f 0102 0304 0506 0708 090a 0b0c 0d0e 0f10 0123 0405 0607 0809 0a0b 0c0d 0e0f 0102 0304 0506 0708 090a 0b0c 0d0e 0f10 0123 0405 0607 0809 0a0b 0c0d 0e0f 0102 0304 0506 0708 090a 0b0c 0d0e 0f10 0123 0405 0607 0809 0a0b 0c0d 0e0f 0102 0304 0506 0708 090a 0b0c 0d0e 0f10 0123 0405 0607 0809 0a0b 0c0d 0e0f 0102 0304 0506 0708 090a 0b0c 0d0e 0f10 0123 0405 0607 0809 0a0b 0c0d 0e0f 0102 0304 0506 0708 090a 0b0c 0d0e 0f10 0123 0405 0607 0809 0a0b 0c0d 0e0f 0102 0304 0506 0708 090a 0b0c 0d0e 0f10 0123 0405 0607 0809 0a0b 0c0d 0e0f 0102 0304 0506 0708 090a 0b0c 0d0e 0f10 0123 0405 0607 0809 0a0b 0c0d 0e0f 0102 0304 0506 0708 090a 0b0c 0d0e 0f10 0123 0405 0607 0809 0a0b 0c0d 0e0f 0102 0304 0506 0708 090a 0b0c 0d0e 0f10 0123 0405 0607 0809 0a0b 0c0d 0e0f 0102 0304 0506 0708 090a 0b0c 0d0e 0f10 0123
```

2. Run the ENET_QoS test case on i.MX 8M Plus EVK.
This use case is only supported on Zephyr.

```
# harpoon_ctrl ethernet -r 1
```

One possible way to verify that the use case is functional is to plug an Ethernet cable on the Ethernet connector on one end, and to a Linux host computer on the other end. Use the `tcpdump` tool on the Linux host to verify that the packets are received correctly.

The expected output on the inmate cell console is as follows:

```
INFO: main_task : Industrial application started!
INFO: industrial_set_hw_addr: 00:bb:cc:dd:ee:14
INFO: enet_qos_init : enet_qos_init
INFO: ethernet_sdk_enet_run :
INFO: ethernet_sdk_enet_run : #
INFO: ethernet_sdk_enet_run : #
INFO: ethernet_sdk_enet_run : #
INFO: ethernet_sdk_enet_run : Wait for PHY init...
```

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30 frames ----> will be sent in 3 queues, and frames will be received in 3 queues.
INFO: ethernet_sdk_enet_run : The frames transmitted from the ring 0, 1, 2 is 10, 10, 10, total 30 frames!
INFO: ethernet_sdk_enet_run : The frames received from the ring 0, 1, 2 is 0, 0, 0, total 0 frames!
INFO: ethernet_sdk_enet_run : ENET QOS TXRX Test Done

3. Run the ENET_QoS Loopback test case on i.MX 8M Plus EVK.
This use case is only supported on Zephyr.

```bash
# harpoon_ctrl ethernet -r 2
```

For this test case, the PHY internal loopback is enabled, so the packets sent out by the ENET_QoS port will be loopbacked and the port will received these packets transmitted.

The expected output on the inmate cell console is as follows:

INFO: main_task : Industrial application started!
INFO: industrial_set_hw_addr: 00:bb:cc:dd:ee:14
INFO: enet_qos_init : enet_qos_init
INFO: ethernet_sdk_enet_run :
INFO: ethernet_sdk_enet_run : #
INFO: ethernet_sdk_enet_run : # enet_qos_app #
INFO: ethernet_sdk_enet_run : #
INFO: ethernet_sdk_enet_run : PHY setup was finalized
INFO: ethernet_sdk_enet_run :
30 frames ----> will be sent in 3 queues, and frames will be received in 3 queues.
INFO: ethernet_sdk_enet_run : The frames transmitted from the ring 0, 1, 2 is 10, 10, 10, total 30 frames!
INFO: ethernet_sdk_enet_run : The frames received from the ring 0, 1, 2 is 10, 10, 10, total 30 frames!
INFO: ethernet_sdk_enet_run : ENET QOS TXRX Loopback Test PASSED

4.5.3.3 Ethernet with GenAVB/TSN stack

A more complex Ethernet use case uses the GenAVB/TSN Stack, which provides advanced implementation for AVB as well as Time-Sensitive Networking (TSN) functionalities. Some functions for the latter do require special TSN hardware support, available in the i.MX 8M Plus SoC for instance.

The following sections give some details on the hardware requirements, setup preparation, and test execution.

As far as the Harpoon demonstration goes, the controller (i.MX 8M Plus) runs in the Cortex-A53 FreeRTOS cell. The IO devices, which can be any TSN endpoint (i.MX 8M Plus, RT1170, etc.) and the TSN bridge complete the TSN network environment for this use case.

4.5.3.3.1 Requirements

- Two TSN endpoints (i.MX 8M Plus LPDDR4 EVK, or optionally an i.MX RT1170 EVK)
- One TSN bridge (LS1028ARDB)

**Note:** The second IO Device is optional.
4.5.3.3.2 Setup preparation

One of the TSN endpoint needs to be configured as “controller” and the other one as “IO device”. Both endpoints are connected to the TSN bridge.

4.5.3.3.2.1 i.MX RT1170 TSN Endpoint - IO Device (Optional)

If using an i.MX RT1170 as the IO device, first flash the latest GenAVB/TSN Endpoint image (https://mcuxpresso.nxp.com/en/dashboard?download=84124a72b3f5916f99168a06ef287f2f).

Once the RT1170 is flashed, press ‘insert’ and set the following parameters:

```
IO_DEVICE_0>>write tsn_app/role 1
IO_DEVICE_0>>write tsn_app/period_ns 100000
```

Press ‘insert’ to exit the configuration mode and reboot.

4.5.3.3.2.2 TSN Bridge

LS1028ARDB can be used as a generic time-aware bridge, connected to other time-aware end stations or bridges.

By default, LS1028ARDB does not forward packets if no bridge interface is configured under Linux. Enabling bridge interface is dependent on the board used.
TSN Bridge Configuration

Use the following commands to configure bridge on LS1028ARDB:

```
# ls /sys/bus/pci/devices/0000:00:00.5/net/
```

Get switch device interfaces for swp0, swp1, swp2, and swp3 as shown below:

```
ip link set dev eno2 up
ip link add name br0 type bridge
ip link set br0 up
ip link set master br0 swp0 up
ip link set master br0 swp1 up
ip link set master br0 swp2 up
ip link set master br0 swp3 up
```

Then start gPTP:

```
# tsn.sh start
```

**TSN Bridge logging**

Logs are stored in `/var/log/tsn-br`.

- **Linux command:**
  
  ```
  # tail -f /var/log/tsn-br
  ```

- The bridge stack statistics are similar to the endpoint stack ones except that they are reported for each of the external ports of the switch (Port 0 to 3) and also for the internal port connected to the endpoint stack (Port 4) in case of Hybrid setup.

- **Pdelay** (propagation delay), **Link status**, **AS capability** and **Port Role** are printed for each port.

```
<table>
<thead>
<tr>
<th>Port(0): domain(0, 0): Role: Master</th>
<th>Link: Up</th>
<th>asCapable: Yes</th>
<th>neighborGptpCapable: Yes</th>
</tr>
</thead>
<tbody>
<tr>
<td>delayMechanism: P2P</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Port(0): Propagation delay (ns): 334.29</td>
<td>min 329</td>
<td>avg 333</td>
<td>max 342 variance 17</td>
</tr>
<tr>
<td>Port(1): domain(0, 0): Role: Disabled</td>
<td>Link: Down</td>
<td>asCapable: No</td>
<td>neighborGptpCapable: No</td>
</tr>
<tr>
<td>delayMechanism: P2P</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Port(2): domain(0, 0): Role: Master</td>
<td>Link: Up</td>
<td>asCapable: Yes</td>
<td>neighborGptpCapable: Yes</td>
</tr>
<tr>
<td>delayMechanism: P2P</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Port(2): Propagation delay (ns): 386.54</td>
<td>min 380</td>
<td>avg 385</td>
<td>max 390 variance 9</td>
</tr>
<tr>
<td>Port(3): domain(0, 0): Role: Disabled</td>
<td>Link: Down</td>
<td>asCapable: No</td>
<td>neighborGptpCapable: No</td>
</tr>
<tr>
<td>delayMechanism: P2P</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Port(4): domain(0, 0): Role: Disabled</td>
<td>Link: Down</td>
<td>asCapable: No</td>
<td>neighborGptpCapable: No</td>
</tr>
<tr>
<td>delayMechanism: P2P</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

If a port is not connected, **Link** status takes the value **Down**.

If a port is not capable of communicating a synchronized time, **AS_Capable** status takes the value **No**.

### 4.5.3.3.3 Running the TSN use case

To start the Ethernet use case from the inmate cell (acting as a TSN Endpoint - Controller), type the following command:

```
# harpoon_ctrl ethernet -r 0
```
To start the Ethernet use case from the inmate cell (acting as a TSN Endpoint - IO Device), type the following command:

```
# harpoon_ctrl ethernet -r 0 -i 0
```

The expected output in the inmate console is:

```
INFO: main_task             : Industrial application started!

INFO: ethernet_avb_tsn_init : ethernet_avb_tsn_init
INFO                     0 app gavb_stack_init : talker_entity_id 0x0000000000000000
INIT                    0.000000000 stack-freertos genavb_init  : NXP's GenAVB/TSN stack
version dev-d71ce4fc
INIT                    0.000000000 stack-freertos hw_avb_timer_init  : hw_timer_init done
INIT                    0.000000000 stack-freertos hw_clock_init  : rate: 24000000, period:
100000000, mult(to ns): 699050667, shift(to ns): 24, mult(to cycles): 103079215, shift(to cycles): 32
INIT                    0.000000000 stack-freertos hw_clock_register  : hw clock id: 1
registered
INIT                    0.000000000 stack-freertos hw_timer_register  : hw_timer(C0600080) of
clock id: 1 registered
INIT                    0.000000000 stack-freertos hw_timer_register  : hw_timer(C06000C8) of
clock id: 1 registered
INIT                    0.000000000 stack-freertos hw_timer_register  : hw_timer(C0600110) of
clock id: 1 registered
INFO                    0.000000000 stack-freertos hw_avb_timer_register_device : dev(C06003D0), ref
clock 24000000 Hz, min delay cycles 240
INFO                    0.000000000 stack-freertos gpt_hw_timer_set_period  : gpt_dev (C06003A0) set
period 125(us), 3000(cycles)
INIT                    0.000000000 stack-freertos __port_init                     : port(0): C0604DF8
INIT                    0.000000000 stack-freertos enet_qos_init              : port(0) enet(0) clock: 125000000 Hz, ptp ref clock: 100000000 Hz, ptp/system clock: 80000000 Hz
INIT                    0.000000000 stack-freertos gpt_init              : gpt_init : registered
GPT HW timer(C06003D0) channel: 0, prescale: 1
ERR                     0.000000000 stack-freertos gpt_init  : gpt_init : failed to
register GPT media clock recovery
INIT                    0.000000000 stack-freertos __port_init                     : port(0): C0604DF8
INIT                    0.000000000 stack-freertos enet_qos_init              : port(0) enet(0) core
clock: 125000000 Hz, ptp ref clock: 100000000 Hz, ptp/system clock: 80000000 Hz
INIT                    0.000000000 stack-freertos gpt_init              : gpt_init : registered
ERR                     0.000000000 stack-freertos hw_avb_timer_register_device : dev(C06003D0), ref
clock 24000000 Hz, min delay cycles 240
```

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ERR 0.000000000 stack-freertos_os_clock_init : clock ID: 12 has no hw
clock
ERR 0.000000000 stack-freertos_os_clock_init : clock ID: 13 has no hw
INIT 0.000000000 stack-freertos_os_clock_init : clock ID: 14 success,
flags: 4
clock
ERR 0.000000000 stack-freertos_os_clock_init : clock ID: 15 has no hw
clock
INFO 0.000000000 stack-freertos_net_qos_map_traffic_class_to_hw_ : port(0) num tc: 5, num
queues: 5, num hw queues: 5, num hw cbs: 2
INFO 0.000000000 stack-freertos_net_qos_map_traffic_class_to_hw_ : tc(0)->hw_queue_id: 0, flags: 2, hw queue prop: 1
INFO 0.000000000 stack-freertos_net_qos_map_traffic_class_to_hw_ : tc(1)->hw_queue_id: 1, flags: 2, hw queue prop: 1
INFO 0.000000000 stack-freertos_net_qos_map_traffic_class_to_hw_ : tc(2)->hw_queue_id: 2, flags: 2, hw queue prop: 1
INFO 0.000000000 stack-freertos_net_qos_map_traffic_class_to_hw_ : tc(3)->hw_queue_id: 3, flags: 2, hw queue prop: 1
INFO 0.000000000 stack-freertos_net_qos_map_traffic_class_to_hw_ : tc(4)->hw_queue_id: 4, flags: 2, hw queue prop: 2
INFO 0.000000000 stack-freertos_hw_timer_request : hw_timer(C0600110)
INFO 0.000000000 stack-freertos_os_timer_create : os_timer(C0626B78), queue: 0
INIT 0.000000000 stack-freertos_net_tx_task : networking(C060F2A8) tx task started
INIT 0.000000000 stack-freertos_net_rx_task : networking(C060F2A8) rx task started
INIT 0.000000000 stack-freertos_timer_system_create : os_timer(C0605A68), queue: 0
INFO 0.000000000 stack-freertos_os_timer_create : os_timer(C0605A68), queue: 0
INIT 0.000000000 stack-freertos_hw_avb_timer_start : hw_timer_start done
INIT 0.000000000 stack-freertos_management_task : management task started
INFO 0.000000000 stack-freertos__net_tx_init : socket(C06585A0), port_id(0)
success
INFO 0.000000000 stack-freertos_ipc_tx_init : ipc(C06039C8, C0658A40)
success
INFO 0.000000000 stack-freertos_ipc_rx_init : ipc(C06039C8, C0658A40)
success
INFO 0.000000000 stack-freertos_timer_system_create : os_timer(C06585A0), queue: 0
INFO 0.000000000 stack-freertos_os_timer_create : os_timer(C06585A0), queue: 0
INIT 0.000000000 management_mac_service_init : mac(C06585D8) done
INIT 0.000000000 management_management_Init : management(C06585D8) done
INIT 0.000000000 stack-freertos_management_task : management task started
INIT 0.000000000 stack-freertos_phy_task : phy task started
INIT 0.000000000 stack-freertos_management_task_init : management main completed
INIT 0.000000000 gtp_gtp_init : gtp task started
INFO 0.000000000 gtp_gtp_check_config : gtp config is valid
INIT 0.000000000 gtp_gtp_init : gtp(task(C065A150)) (profile 0 -
async 0 - num ports = 1 - force_2011 = 0)
success
INIT 0.000000000 stack-freertos_ipc_tx_init : ipc(C0602B88, C0665F40)
success
success
INFO 0.000000000 stack-freertos_ipc_rx_init : ipc(C0602B88, C0665F40)
port_id(0)
INFO 0.000000000 stack-freertos__net_rx_init : socket(C0666280)
INFO 0.000000000 stack-freertos__net_tx_init : socket(C06664A0)
INFO 0.000000000 stack-freertos_net_add_multi : port(0)
01:80:c2:00:00:0e
INFO 0.000000000 stack-freertos_timer_system_create : os_timer(C0665530), queue: 0
INFO 0.000000000 stack-freertos_os_timer_create : os_timer(C0665530), queue: C0659FA0
```
<table>
<thead>
<tr>
<th>Level</th>
<th>Time</th>
<th>Message</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>INIT</td>
<td>0.000000000</td>
<td>gptp gptp_instance_init</td>
<td>: Configuring Port(0) (C0664AB0)</td>
</tr>
<tr>
<td>INIT</td>
<td>0.000000000</td>
<td>gptp gptp_port_init_timers</td>
<td>: Port(0)</td>
</tr>
<tr>
<td>INFO</td>
<td>0.000000000</td>
<td>stack-freertos timer_system_create</td>
<td>: os_timer(C0665A10), queue: C0659FA0</td>
</tr>
<tr>
<td>INFO</td>
<td>0.000000000</td>
<td>stack-freertos os_timer_create</td>
<td>: os_timer(C0665A10), queue: C0659FA0</td>
</tr>
<tr>
<td>INFO</td>
<td>0.000000000</td>
<td>stack-freertos timer_system_create</td>
<td>: os_timer(C0665A78), queue: C0659FA0</td>
</tr>
<tr>
<td>INFO</td>
<td>0.000000000</td>
<td>stack-freertos os_timer_create</td>
<td>: os_timer(C0665A78), queue: C0659FA0</td>
</tr>
<tr>
<td>INFO</td>
<td>0.000000000</td>
<td>stack-freertos timer_system_create</td>
<td>: os_timer(C0665AE0), queue: C0659FA0</td>
</tr>
<tr>
<td>INFO</td>
<td>0.000000000</td>
<td>stack-freertos os_timer_create</td>
<td>: os_timer(C0665AE0), queue: C0659FA0</td>
</tr>
<tr>
<td>INFO</td>
<td>0.000000000</td>
<td>stack-freertos timer_system_create</td>
<td>: os_timer(C0665B48), queue: C0659FA0</td>
</tr>
<tr>
<td>INFO</td>
<td>0.000000000</td>
<td>stack-freertos os_timer_create</td>
<td>: os_timer(C0665B48), queue: C0659FA0</td>
</tr>
<tr>
<td>INFO</td>
<td>0.000000000</td>
<td>stack-freertos timer_system_create</td>
<td>: os_timer(C0665B18), queue: C0659FA0</td>
</tr>
<tr>
<td>INFO</td>
<td>0.000000000</td>
<td>stack-freertos os_timer_create</td>
<td>: os_timer(C0665B18), queue: C0659FA0</td>
</tr>
<tr>
<td>INFO</td>
<td>0.000000000</td>
<td>stack-freertos timer_system_create</td>
<td>: os_timer(C0665B80), queue: C0659FA0</td>
</tr>
<tr>
<td>INFO</td>
<td>0.000000000</td>
<td>stack-freertos os_timer_create</td>
<td>: os_timer(C0665B80), queue: C0659FA0</td>
</tr>
<tr>
<td>INFO</td>
<td>0.000000000</td>
<td>stack-freertos timer_system_create</td>
<td>: os_timer(C0665CE8), queue: C0659FA0</td>
</tr>
<tr>
<td>INFO</td>
<td>0.000000000</td>
<td>stack-freertos os_timer_create</td>
<td>: os_timer(C0665CE8), queue: C0659FA0</td>
</tr>
<tr>
<td>ERR</td>
<td>0.000000000</td>
<td>common timer_start</td>
<td>: timer(C0664F58) 0ms period</td>
</tr>
<tr>
<td>INFO</td>
<td>0.000000000</td>
<td>stack-freertos timer_system_create</td>
<td>: os_timer(C0665D50), queue: C0659FA0</td>
</tr>
<tr>
<td>INFO</td>
<td>0.000000000</td>
<td>stack-freertos os_timer_create</td>
<td>: os_timer(C0665D50), queue: C0659FA0</td>
</tr>
<tr>
<td>INIT</td>
<td>0.000000000</td>
<td>gptp gptp_instance_init</td>
<td>: instance(C0664570) domain(1, -1)</td>
</tr>
<tr>
<td>INIT</td>
<td>0.000000000</td>
<td>gptp gptp_link_down</td>
<td>: Port(0): link is DOWN</td>
</tr>
<tr>
<td>INFO</td>
<td>0.000000000</td>
<td>srp msrp_map_init</td>
<td>: done</td>
</tr>
<tr>
<td>INIT</td>
<td>0.159357387</td>
<td>srp srp_task</td>
<td>: gptp main completed</td>
</tr>
<tr>
<td>INIT</td>
<td>0.159357387</td>
<td>srp srp_task_start</td>
<td>: srp task started</td>
</tr>
<tr>
<td>INIT</td>
<td>0.159357387</td>
<td>stack-freertos ipx_tx_init</td>
<td>: ipc(C0602A58, C0666DC0)</td>
</tr>
<tr>
<td>INIT</td>
<td>0.159357387</td>
<td>stack-freertos ipx_rx_init</td>
<td>: ipc(C06069B0, C066B80)</td>
</tr>
<tr>
<td>INIT</td>
<td>0.159357387</td>
<td>stack-freertos _net_rx_init</td>
<td>: socket(C0606B92O)</td>
</tr>
<tr>
<td>INIT</td>
<td>0.159357387</td>
<td>stack-freertos _net_tx_init</td>
<td>: socket(C0606B40)</td>
</tr>
<tr>
<td>INIT</td>
<td>0.159357387</td>
<td>stack-freertos ipx_tx_init</td>
<td>: ipc(C06069B80, C066B780)</td>
</tr>
<tr>
<td>INIT</td>
<td>0.159357387</td>
<td>stack-freertos ipx_rx_init</td>
<td>: ipc(C06014FA, C066BF0)</td>
</tr>
<tr>
<td>INIT</td>
<td>0.159357387</td>
<td>stack-freertos ipx_tx_init</td>
<td>: ipc(C0601628, C066C0AD0)</td>
</tr>
<tr>
<td>INIT</td>
<td>0.159357387</td>
<td>stack-freertos ipx_rx_init</td>
<td>: ipc(C060175B, C066C240)</td>
</tr>
<tr>
<td>INIT</td>
<td>0.159357387</td>
<td>stack-freertos ipx_tx_init</td>
<td>: ipc(C060175B, C066C240)</td>
</tr>
</tbody>
</table>
```
INIT  0.159357387 srp  msrp_port_init          : port(0) done
INFO  0.159357387 srp  msrp_create_domain    : port(0) domain(6, 3, 2)
INFO  0.159357387 stack-freertos  timer_system_create : os_timer(C066B458),
queue: C0667BF0
INFO  0.159357387 srp  mrp_alloc_attribute  : mrp_app(C066AD40) port(0)
INFO  0.159357387 srp  mrp_mad_join_request : mrp_app(C066AD40) port(0)
INFO  0.159357387 stack-freertos  os_timer_create : os_timer(C066B458),
queue: C0667BF0
INFO  0.159357387 srp  msrp_domain_update_boundary_port : port(0) class(2), srp boundary
1
INFO  0.159357387 srp  msrp_domain_update_boundary_port : port(0) class(1), srp boundary
1
INFO  0.159357387 stack-freertos  net_add_multi         : port(0)
INFO  0.159357387 srp  msrp_port_enable          : port(0) enabled
INFO  0.159357387 srp  msrp_enable              : msrp(C066ABB8) enabled
INFO  0.159357387 stack-freertos  ipc_rx_init        : ipc(C0601C18, C066C470)
success
INFO  0.159357387 stack-freertos  ipc_tx_init        : ipc(C0601D48, C066C610)
success
INFO  0.159357387 stack-freertos  ipc_tx_init        : ipc(C0601E78, C066C7B0)
success
INFO  0.159357387 stack-freertos  ipc_tx_init        : ipc(C0601AD8, C066C9B0)
success
INFO  0.159357387 stack-freertos  ipc_tx_init        : ipc(C0601BD8, C066CB10)
success
INFO  0.159357387 stack-freertos  mvrp_port_init       : port(0) done
INFO  0.159357387 stack-freertos  mvrp_init           : mvrp(C066B010) done
INFO  0.159357387 stack-freertos  mmrp_init           : mmrp(C066AB38) done
INFO  0.159357387 stack-freertos  srp_init            : srp(C0667DA0) done
INFO  0.159357387 stack-freertos  srp_port_status      : started
INFO  0.159357387 srp  mrp_port_status          : msrp(C066ABB8) port(0)
operational (0)
INFO  0.159357387 srp  mvrp_port_status         : mvrp(C066B010) port(0)
operational (0)
INFO  0.159357387 stack-freertos  phy_task         : phy(1) initialized
INFO  0.159357387 stack-freertos  srp_task_init     : srp main completed
INFO: ethernet_avb_tsn_run : tsn_app config
INFO: ethernet_avb_tsn_run : mode : NETWORK_ONLY
INFO: ethernet_avb_tsn_run : role     : 0 ;
INFO: ethernet_avb_tsn_run : num_io_devices : 1
INFO: ethernet_avb_tsn_run : motor_offset : 0
INFO: ethernet_avb_tsn_run : control_strategy : 0
INFO: ethernet_avb_tsn_run : app_period : 100000
INFO: ethernet_avb_tsn_run : BUILD MOTOR disabled, MOTOR_NETWORK and MOTOR_LOCAL modes cannot be
used
INFO  0.159357387 stack-freertos  hw_timer_request      : hw_timer(C06059B0) pps
INFO  0.159357387 stack-freertos  os_timer_create    : os_timer(C06532B0)
queue: 0
INFO  0 app  gavb_pps_init              : success, clk_id: 1
INFO  0 app cycle_task_init            : cyclic task type: 0, id: 0
INFO  0 app cycle_task_init            : task params
INFO  0 app cycle_task_init            : task_period_ns : 100000
To stop the Ethernet use case (to eventually restart it), the previous run must be stopped with the following command:

```
# harpoon_ctrl ethernet -s
```

### 4.6 rt_latency application

The rt_latency application is a simple benchmark application for real-time OS that measures the latency (Time delta, in nanoseconds) between hardware IRQ events and software actions:

- **irq delay**: time to enter in the software IRQ handler after a hardware IRQ occurs (hardware + hypervisor + IRQ vector latency)
- **irq to sched**: time to enter in an RTOS task, scheduled by the IRQ handler (irq delay + RTOS scheduler)

All measurements are done using a hardware timer (GPT on i.MX 8M or TPM on i.MX 93) and relative to the hardware IRQ event time, with sub-microsecond precision.

Since Harpoon 2.4, the timer sampling frequency has been increased to better reflect real-time constraints: The hardware timer is now scheduled every 100 us.

When running, the rt_latency application prints regular statistics, based on the measurements taken, to help characterize the system real-time latency.

The rt_latency application is available in the Harpoon share directory of the root file system:

```
/usr/share/harpoon/inmates/freertos/rt_latency.bin  # FreeRTOS binary
/usr/share/harpoon/inmates/zephyr/rt_latency.bin    # Zephyr binary
```
To use the `rt_latency` application, Jailhouse must be started first. To start Jailhouse and the `rt_latency` application, create an appropriate Harpoon configuration file and run the Harpoon service with `systemd`. For instance:

```
# harpoon_set_configuration.sh freertos latency
# systemctl start harpoon
```

The Harpoon service uses the `/etc/harpoon/harpoon.conf` configuration file that contains the RTOS and the application to run. By default, the configuration file points to the FreeRTOS audio application. To run the `rt_latency` application, we have generated a corresponding configuration file. This step needs to be run only once.

Once the Harpoon service has been started, the following `rt_latency` trace is shown in the terminal emulator connected to the other serial port:

```
Harpoon v2.4.0
main_task: running
```

After booting, the `rt_latency` application waits for commands to be received. A list of available commands is shown using the command `harpoon_ctrl`:

```
# harpoon_ctrl -h
```

The usage for the `rt_latency` application is shown:

<table>
<thead>
<tr>
<th>Latency options:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><code>-r &lt;id&gt;</code></td>
<td>run latency test case id</td>
</tr>
<tr>
<td><code>-s</code></td>
<td>stop running test case</td>
</tr>
</tbody>
</table>

Examples:

To stop the `rt_latency` application’s current test case:

```
# harpoon_ctrl latency -s
```

To run a test case:

It is possible to engage some CPU load and/or IRQ load to measure their impact on the latency. To do so, different test cases (TC) can be executed, by specifying the test case id with the “-r” option:

```
# harpoon_ctrl latency -r <TC_ID>
```

TC_ID:

- 1: no extra load
- 2: extra CPU load (low-priority task, executing busy loop and consuming all available CPU time)
- 3: extra IRQ load
- 4: extra CPU load + semaphore load
- 5: extra CPU load + Linux load (not provided by the test case)
- 6: extra CPU load + cache flush (instruction cache only for this release)

To execute test case 1:

```
# harpoon_ctrl latency -r 1
```
When running, latency statistics are printed every 10 seconds:

---
INFO: start_test_case : Running test case 1:
INFO: benchmark_task : running
INFO: stats_print : stats(C0601B30) irq delay (ns) min 625 mean 792 max 3625 rms^2 629985 stddev^2 1510 absmin 625 absmax 3625
INFO: hist_print : n_slot 21 slot_size 1000
INFO: hist_print : 99890 76 22 12 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
INFO: stats_print : stats(C0601F90) irq to sched (ns) min 2583 mean 2587 max 8291 rms^2 6702537 stddev^2 6329 absmin 2583 absmax 8291
INFO: hist_print : n_slot 21 slot_size 1000
INFO: hist_print : 0 0 99673 233 68 22 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
INFO: print_stats : late alarm scheduling: 0

Both the irq delay and the irq to sched statistics are shown:

- min/mean/max: minimum, average and maximum latency value measured within the last period of time
- absmin/absmax: minimum and maximum latency value measured since the beginning of the test
- A histogram is also shown to give an idea of repartition of the measured latency values

Table 10. Real-time latencies measured on i.MX 93/FreeRTOS (in ns)

<table>
<thead>
<tr>
<th>Description</th>
<th>i.MX 93 IRQ Latency (ns)</th>
<th>i.MX 93 Task Latency (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Average</td>
</tr>
<tr>
<td>No system load</td>
<td>500</td>
<td>708</td>
</tr>
<tr>
<td>Low priority task CPU load</td>
<td>500</td>
<td>689</td>
</tr>
<tr>
<td>Low priority IRQ load</td>
<td>7,250</td>
<td>9,254</td>
</tr>
<tr>
<td>Low priority task CPU load, mutex</td>
<td>500</td>
<td>708</td>
</tr>
<tr>
<td>Linux CPU + memory load</td>
<td>500</td>
<td>689</td>
</tr>
<tr>
<td>RTOS cold cache</td>
<td>500</td>
<td>689</td>
</tr>
</tbody>
</table>

Table 11. Real-time latencies measured on i.MX 8M Plus/FreeRTOS (in ns)

<table>
<thead>
<tr>
<th>Test description</th>
<th>i.MX 8M Plus IRQ Latency (ns)</th>
<th>i.MX 8M Plus Task Latency (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Average</td>
</tr>
<tr>
<td>No system load</td>
<td>583</td>
<td>793</td>
</tr>
<tr>
<td>Low priority task CPU load</td>
<td>583</td>
<td>793</td>
</tr>
<tr>
<td>Low priority IRQ load</td>
<td>7,485</td>
<td>11,205</td>
</tr>
</tbody>
</table>

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Table 11. Real-time latencies measured on i.MX 8M Plus/FreeRTOS (in ns)...continued

<table>
<thead>
<tr>
<th>Test description</th>
<th>i.MX 8M Plus IRQ Latency (ns)</th>
<th>i.MX 8M Plus Task Latency (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Average</td>
</tr>
<tr>
<td>Low priority task CPU load, mutex</td>
<td>583</td>
<td>793</td>
</tr>
<tr>
<td>Linux CPU + memory load</td>
<td>583</td>
<td>793</td>
</tr>
<tr>
<td>RTOS cold cache</td>
<td>583</td>
<td>793</td>
</tr>
</tbody>
</table>

Table 12. Real-time latencies measured on i.MX 93/Zephyr (in ns)

<table>
<thead>
<tr>
<th>Description</th>
<th>i.MX 93 IRQ Latency (ns)</th>
<th>i.MX 93 Task Latency (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Average</td>
</tr>
<tr>
<td>No system load</td>
<td>541</td>
<td>708</td>
</tr>
<tr>
<td>Low priority task CPU load</td>
<td>541</td>
<td>708</td>
</tr>
<tr>
<td>Low priority IRQ load</td>
<td>541</td>
<td>787</td>
</tr>
<tr>
<td>Low priority task CPU load, mutex</td>
<td>541</td>
<td>708</td>
</tr>
<tr>
<td>Linux CPU + memory load</td>
<td>541</td>
<td>708</td>
</tr>
<tr>
<td>RTOS cold cache</td>
<td>541</td>
<td>708</td>
</tr>
</tbody>
</table>

Table 13. Real-time latencies measured on i.MX 8M Plus/Zephyr (in ns)

<table>
<thead>
<tr>
<th>Description</th>
<th>i.MX 8M Plus IRQ Latency (ns)</th>
<th>i.MX 8M Plus Task Latency (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Average</td>
</tr>
<tr>
<td>No system load</td>
<td>666</td>
<td>867</td>
</tr>
<tr>
<td>Low priority task CPU load</td>
<td>666</td>
<td>859</td>
</tr>
<tr>
<td>Low priority IRQ load</td>
<td>625</td>
<td>1,077</td>
</tr>
<tr>
<td>Low priority task CPU load, mutex</td>
<td>666</td>
<td>871</td>
</tr>
<tr>
<td>Linux CPU + memory load</td>
<td>666</td>
<td>859</td>
</tr>
<tr>
<td>RTOS cold cache</td>
<td>666</td>
<td>860</td>
</tr>
</tbody>
</table>

4.7 Virtio Networking application
4.7.1 Features of the Virtio Networking application

The `virtio_net` application is available in the Harpoon share directory of the root file system:

```
/usr/share/harpoon/inmates/freertos/virtio_net.bin  # FreeRTOS binary
```

**Note:** In the current release, the `virtio_net` application is only supported under FreeRTOS on i.MX 8M Mini EVK, i.MX 8M Plus EVK or i.MX 93 EVK for Yocto Real-time Edge SW (i.MX BSP Yocto not supported).

This application starts a Virtio networking back end on Jailhouse inmate cell. Linux OS runs Virtio networking front end, which provides a virtual network interface. The back end owns physical ENET port and shares with the front end by using Virtio communication between the front end and back end.

4.7.2 Running the Virtio Networking application

To use the `virtio_net` application, Jailhouse must be started first. To start Jailhouse and the Virtio Networking application, create the corresponding Harpoon configuration file and run the Harpoon service using `systemd`, for example:

```
# harpoon_set_configuration.sh freertos virtio_net
```

**Note:** Avoid changing the configuration while the Harpoon service is running (silent failure when restarting the service).

The configuration file is stored under `/etc/harpoon/harpoon.conf` and the Harpoon systemd service uses it to start Jailhouse and the Virtio Networking application:

```
# systemctl start harpoon
```

When the Harpoon service has been started, `virtio_net` back end application is started with the following login console of inmate cell:

```
Starting Virtio networking backend...
virtio network device initialization succeed!
Switch enabled with enet remote port succeed!
ENET: PHY link is up with speed 1000M full-duplex
```

Then in Linux console of root cell, use `ifconfig` and `ethtool` to check whether virtual networking interface is available. The driver used by virtual networking interface is "virtio_net", so from the following log, "eth1" is Virtio virtual networking interface.

```
root@imx8mm-lpddr4-evk:~# ifconfig
eth0: flags=4163<UP,BROADCAST,RUNNING,MULTICAST> mtu 16384
       ether fa:6f:22:ce:31:6b  txqueuelen 1000  (Ethernet)
       RX packets 0  bytes 0 (0.0 B)
       RX errors 0  dropped 0  overruns 0  frame 0
       TX packets 0  bytes 0 (0.0 B)
       TX errors 0  dropped 0  overruns 0  carrier 0  collisions 0

eth1: flags=4163<UP,BROADCAST,RUNNING,MULTICAST> mtu 1500
       inet 10.193.20.30  netmask 255.255.255.0  broadcast 10.193.20.255
       inet6 fe80::201:2ff:fe03:405  prefixlen 64  scopeid 0x20<link>
       ether 00:04:9f:00:01:02  txqueuelen 1000  (Ethernet)
       RX packets 17  bytes 3897 (3.8 Kib)
       RX errors 0  dropped 0  overruns 0  frame 0
       TX packets 41  bytes 7309 (7.1 Kib)
       TX errors 0  dropped 0  overruns 0  carrier 0  collisions 0
```
lo: flags=73<UP,LOOPBACK,RUNNING>  mtu 65536
     inet 127.0.0.1  netmask 255.0.0.0
     inet6 ::1  prefixlen 128  scopeid 0x10<host>
     loop txqueuelen 1000  (Local Loopback)
     RX packets 99  bytes 8926 (8.7 KiB)
     RX errors 0  dropped 0  overruns 0  frame 0
     TX packets 99  bytes 8926 (8.7 KiB)
     TX errors 0  dropped 0  overruns 0  carrier 0  collisions 0

root@imx8mm-lpddr4-evk:~# ethtool -i eth1
deriver: virtio_net
version: 1.0.0
firmware-version:
expansion-rom-version:
buss-info: b9400000.virtio_net
supports-statistics: yes
supports-test: no
supports-eprom-access: no
supports-register-dump: no
supports-priv-flags: no

If the interface is connected to a DHCP service, it gets the IP address by DHCP. Otherwise, set the IP address by using the `ifconfig` command.

Then use the `ping` command to check whether the virtual networking interface works or not.

root@imx8mm-lpddr4-evk:~# ping 10.193.20.18
PING 10.193.20.18 (10.193.20.18) 56(84) bytes of data.
64 bytes from 10.193.20.18: icmp_seq=1 ttl=64 time=3.65 ms
64 bytes from 10.193.20.18: icmp_seq=2 ttl=64 time=1.83 ms
64 bytes from 10.193.20.18: icmp_seq=3 ttl=64 time=1.83 ms
64 bytes from 10.193.20.18: icmp_seq=4 ttl=64 time=1.83 ms
64 bytes from 10.193.20.18: icmp_seq=5 ttl=64 time=1.84 ms
64 bytes from 10.193.20.18: icmp_seq=6 ttl=64 time=1.84 ms

Use the following command to change the MAC address of `virtio_net`:

root@imx8mm-lpddr4-evk:~# ifconfig eth1 hw ether 00:04:9f:00:01:03

5 Known Issues

<table>
<thead>
<tr>
<th>ID</th>
<th>Description</th>
<th>Workarounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRPN-245</td>
<td>Linux cannot access eMMC.</td>
<td>Store the root file system on SD card or NFS.</td>
</tr>
<tr>
<td>HRPN-448</td>
<td>RTOS crashes on Ethernet TSN use case stress restarts.</td>
<td>Restart the Jailhouse cell.</td>
</tr>
<tr>
<td>HRPN-483</td>
<td>Audio glitches on all boards for combination of high frequency and low frame size.</td>
<td>Do not use combinations of the following parameters:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Frame size: 2, 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Frequency: 176.4 kHz, 192 kHz</td>
</tr>
<tr>
<td>HRPN-632</td>
<td>Occurrences of command timeout for frame size 2 for Audio SMP pipeline.</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 14. Known issues...continued

<table>
<thead>
<tr>
<th>ID</th>
<th>Description</th>
<th>Workarounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRPN-739</td>
<td>Changing the MAC address after restarting the Audio application does not change the AVB Entity ID and may lead to spurious crashes with third-party AVDECC controller.</td>
<td>Restart the Harpoon service.</td>
</tr>
<tr>
<td>HRPN-779</td>
<td>i.MX 8M Plus: Lower audio volume for on-board Jack output compared to HiFiBerry’s output.</td>
<td>-</td>
</tr>
<tr>
<td>HRPN-872/873</td>
<td>When running Audio SMP, you may run into instabilities: for combination of high frequency and low frame size, you might have audio sample drop.</td>
<td>-</td>
</tr>
<tr>
<td>HRPN-895</td>
<td>AVB streaming: spurious and short PTP synchronization loss on long runs.</td>
<td>-</td>
</tr>
</tbody>
</table>

6 Technical Details on Harpoon Applications

6.1 Description

Harpoon reference applications are embedded in a repository named harpoon-apps.

Several RTOS applications are embedded in this repository, which may run in Jailhouse cells, based on an RTOS (currently using FreeRTOS and Zephyr) and leveraging the MCUXpresso SDK. As a consequence, FreeRTOS-Kernel, CMSIS_5 and mcux-sdk repositories are required to build FreeRTOS based applications and zephyr and hal_nxp repositories are required to build Zephyr based applications. Additionally, repository GenAVB_TSN is needed to build the industrial application. The west tool is used to fetch those repositories, along with harpoon-apps Git tree.

To manage Linux - RTOS communication, a control application running in the Linux root cell is used. This application is to be compiled with the Yocto toolchain.

The next section explains how to build binaries (RTOS application and Linux control application).

Related information
https://docs.zephyrproject.org/latest/guides/west/index.html

6.2 Manual build

6.2.1 Setting up the environment

You need to have both git and west installed to fetch the source code for Harpoon-apps, FreeRTOS, Zephyr, MCUXpresso SDK, etc.:

```
$ west init -m https://github.com/NXP/harpoon-apps --mr harpoon_2.4.0 hww
$ cd hww
$ west update
```

6.2.2 Building the RTOS application for the RTOS cell

6.2.2.1 Building FreeRTOS based applications

FreeRTOS applications for Armv8-A must be compiled with a compatible toolchain.

The reference toolchain is the GNU Arm cross-toolchain for the A-profile cores GCC 10.3-2021.07.
To download the toolchain and install it:

```bash
$ wget https://developer.arm.com/-/media/Files/downloads/gnu-a/10.3-2021.07/binrel/gcc-arm-10.3-2021.07-x86_64-aarch64-none-elf.tar.xz
$ tar -C /opt/ -xvf gcc-arm-10.3-2021.07-x86_64-aarch64-none-elf.tar.xz
```

If starting from a fresh console, the cross-compiler variable must be set:

```bash
$ export ARMGCC_DIR=/opt/gcc-arm-10.3-2021.07-x86_64-aarch64-none-elf/
```

Then build an RTOS application:

```bash
$ cd harpoon-apps/<RTOS_APP>/freertos/boards/<BOARD>/armgcc_aarch64
$ ./build_ddr_release.sh
```

Where:

- **RTOS APP** is **hello_world**, **audio**, **industrial** or **rt_latency**.
- **BOARD** is **evkmimx8mm** for **i.MX 8M Mini**, **evkmimx8mn** for **i.MX 8M Nano**, **evkmimx8mp** for **i.MX 8M Plus**, **mcimx93evk** for **i.MX 93 EVK**.
  
  **Note**: In this release, **i.MX 93 EVK only supports the** **hello_world**, **rt_latency** and **Virtio Networking applications**.

- Build artefacts are available in the directory **ddr_release/**.
- The artefact to be used on target is the RTOS application binary: `<RTOS_APP>.bin`

### 6.2.2.2 Building Zephyr based applications

Install cross-compile toolchain first, and then set the cross-compile environment:

```bash
$ export ARMGCC_DIR=/opt/gcc-arm-10.3-2021.07-x86_64-aarch64-none-elf/
```

Then build a Single Core Zephyr application

```bash
$ cd harpoon-apps/<RTOS_APP>/zephyr/boards/<BOARD>/armgcc_aarch64
$ ./build_singlecore.sh
```

Or build an SMP Zephyr application

```bash
$ cd harpoon-apps/<RTOS_APP>/zephyr/boards/<BOARD>/armgcc_aarch64
$ ./build_smp.sh
```

Where,

- **RTOS APP** is **hello_world**, **audio**, **industrial**, or **rt_latency**.
- **BOARD** is **evkmimx8mm** for **i.MX 8M Mini**, **evkmimx8mn** for **i.MX 8M Nano**, **evkmimx8mp** for **i.MX 8M Plus**, **mcimx93evk** for **i.MX 93 EVK**.
  
  **Note**: In this release, **i.MX 93 EVK only supports the** **hello_world** and **rt_latency applications**.

- Build artefacts are available in the directory **build_singlecore/zephyr/** or **build_smp/zephyr/**.
- The artefact to be used on target is the RTOS application binary: `<RTOS_APP>.bin` for singlecore application or `<RTOS_APP>_smp.bin` for SMP application.

### 6.2.3 Building the Linux control application for the root cell

The Linux control application for Armv8-A must be compiled with a compatible toolchain.
The reference toolchain is the Poky Arm cross-toolchain built with Yocto.

To generate this toolchain:

```bash
$ bitbake meta-toolchain
```

This generates a toolchain installer in directory `tmp/deploy/sdk`. The installer name depends on the `DISTRO` and `MACHINE` variables and on the image name of the current build. For instance, for an i.MX build, the installer name is `fsl-imx-xwayland-glibc-x86_64-meta-toolchain-armv8a-imx8mm-lpddr4-evk-toolchain-6.1-mickledore.sh`.

When executed, the installer prompts for a directory where to put the toolchain. The default location for the i.MX toolchain is `/opt/fsl-imx-xwayland/6.1-mickledore`.

When the toolchain is installed, different cross-compile variables must be set. This is done by sourcing script `environment-setup-cortexa53-crypto-poky-linux`. For example with default installation path:

```bash
$ . /opt/fsl-imx-xwayland/6.1-mickledore/environment-setup-armv8a-poky-linux
```

The Harpoon control application can then be built:

```bash
$ cd harpoon-apps/ctrl
$ ./build_ctrl.sh
```

The build generates one binary: `harpoon_ctrl` in the same directory and can be used on target.

The Linux root cell uses the Remote Processor Messaging (RPMsg) device to communicate with FreeRTOS and Zephyr inmate cells. `harpoon_ctrl` binary implements this device, and should be used to communicate with RTOS cells.

### 6.3 Developing a Harpoon Application

Harpoon-apps is the basis to create a Harpoon application. It links with (at least) MCUXpresso drivers and an RTOS (FreeRTOS and Zephyr).

A Harpoon application has its own directory in the root folder of the Harpoon-apps repository. Examples include `audio`, the audio reference application, `industrial`, the industrial reference application and `rt_latency`, the real-time benchmark application.

#### 6.3.1 Architecture of the audio application

The audio application, which serves as an example for this chapter, has the following architecture.
The DAC and ADC on the HiFiBerry card are controlled by the audio application. Control is done through I2C3 and data throughput through SAI5.

6.3.2 Source file creation

This chapter gives some information on how to develop an application for Harpoon by using the audio application as an example.

First, the application directory must be created in the root directory of repository harpoon-apps.

This directory contains the source code for the application, a CMake configuration file listing the files to be compiled. Source file can be common to all RTOS and platform, be RTOS dependent and/or platform dependent. Helper scripts are provided to build the application for each RTOS/platform combination.
The application starts in function `main()`, defined in file `main.c`.

RTOS specific code goes to directory `audio/freertos` and `audio/zephyr`.

Board specific code (clock configuration, hardware description, MMU configuration) goes to directory `audio/<rtos>/boards/<boardid>` and `audio/boards/<boardid>`.

OS-agnostic code goes to directory `audio/common`.

### 6.3.3 Board specific code

Board specific code and header files for the audio application include:

<table>
<thead>
<tr>
<th>File</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>app_board.h</code></td>
<td>Definition of SAI and I2C instances used for the demo. I2C addresses of HiFiBerry's DAC and ADC. SAI configuration. Audio samples format.</td>
</tr>
<tr>
<td><code>app_mmu.h</code></td>
<td>Device memory to map with MMU (includes SAI and I2C).</td>
</tr>
<tr>
<td><code>sai_clock_config.c</code></td>
<td>Configuration of Audio PLLs, Audiomix (for i.MX 8M Plus) and SAI clocks.</td>
</tr>
<tr>
<td><code>sai_config.c</code></td>
<td>Define configuration of each SAI instance.</td>
</tr>
<tr>
<td><code>codec_config.c</code></td>
<td>Helper functions to open, configure and close DAC and ADC drivers.</td>
</tr>
<tr>
<td><code>pin_mux.c</code></td>
<td>Functions to set IOMux for the application use case.</td>
</tr>
<tr>
<td><code>CMakeLists.txt</code></td>
<td>CMake configuration file that includes all necessary MCUXpresso drivers.</td>
</tr>
<tr>
<td><code>flags.cmake</code></td>
<td>CFLAGS and LDFLAGS definitions for building the application.</td>
</tr>
</tbody>
</table>

### 6.3.4 Controlling application from Linux side

Linux side can control the Harpoon application by sending messages through the RPMsg communication channel.

The audio application leverages this in function `audio_control_init()`, defined in `audio/common/audio.c`.

For RPMsg channel, RTOS creates a RPMsg endpoint with service name "rpmseg-raw" for communication:

```c
audio_ctx->ctrl.ept = rpmsg_transport_init(RL_BOARD_RPMSG_LINK_ID, EPT_ADDR, "rpmseg-raw");
```

Finally, the application's main thread periodically looks for incoming control messages:

```c
do {
```
audio_command_handler(&ctx);
[...]
} while (1);

The Linux user space application that sends control messages is located in the directory `ctrl` of the `harpoon-apps` repository.

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```
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```

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The following table provides the revision history for this document.

<table>
<thead>
<tr>
<th>Revision number</th>
<th>Date</th>
<th>Substantive changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4</td>
<td>28 July 2023</td>
<td>• Full Support for RPMsg control (all OSes, all boards)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Support for RT Latency on i.MX 93</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Support for Virtual Ethernet on i.MX 8M Plus and i.MX 93</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Support for AVB Listener Media Clock Recovery on i.MX 8M Plus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Support for AVB Listener Synchronization</td>
</tr>
<tr>
<td>2.3</td>
<td>28 March 2023</td>
<td>• Support for AVB Talker in FreeRTOS audio</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Support for RPMsg control (FreeRTOS, all boards)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Support for Virtual Ethernet</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Support for i.MX 93 (preview: hello_world)</td>
</tr>
<tr>
<td>2.2</td>
<td>16 December 2022</td>
<td>• Support for AVB listener in FreeRTOS audio</td>
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<tr>
<td></td>
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<td>• Support for SMP pipeline in Zephyr audio</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Support for RPMsg control (preview)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Support for ENET, ENET_QoS in Zephyr industrial</td>
</tr>
<tr>
<td>Revision number</td>
<td>Date</td>
<td>Substantive changes</td>
</tr>
<tr>
<td>-----------------</td>
<td>----------------</td>
<td>--------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>EAR 2.0.0</td>
<td>14 January 2022</td>
<td>Introduction of harpoon-apps, Support of FreeRTOS, Support of both i.MX BSP and Real-Time Edge SW</td>
</tr>
<tr>
<td>EAR 2.0.1</td>
<td>29 March 2022</td>
<td>Full integration to NXP Real-Time Edge</td>
</tr>
</tbody>
</table>
| EAR 2.1.0       | 30 June 2022   | • New industrial application in harpoon-apps                                          
|                 |                | • Implementation of flexible audio pipeline in harpoon-apps                           
|                 |                | • Support for i.MX 8M Nano EVK for i.MX Yocto                                        
|                 |                | • Support for EVK's internal audio codecs                                            
|                 |                | • Support for systemd                                                                
|                 |                | • Support for Zephyr                                                                  
|                 |                | • Drivers for FlexCAN, ENET, ENET_QOS                                                |
| EAR 2.1.0       | 28 July 2022   | Minor changes to Section 4 and Section 5. Compatible with Real-Time Edge Software Rev 2.3 release |

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Contents

1 Overview .............................................................. 2
  1.1 Supported Features ...........................................3
  1.2 Architecture ....................................................4
  1.3 Hardware resource partitioning ..........................4

2 Building Harpoon Yocto images ............................5
  2.1 i.MX Yocto .......................................................6
  2.2 Real-Time Edge Yocto .......................................6

3 Hardware Setup ...................................................6
  3.1 i.MX Reference Boards .....................................6
    3.1.1 i.MX 8M Mini EVK ......................................7
    3.1.2 i.MX 8M Nano EVK ....................................7
    3.1.3 i.MX 8M Plus EVK .....................................8
    3.1.4 i.MX 93 EVK ..............................................8
  3.2 Audio use case hardware ..................................8
  3.3 Industrial use case hardware .............................12
  3.4 Virtio networking use case hardware ....................14

4 Running Harpoon Reference Applications ..................14
  4.1 Basic setup ....................................................14
  4.2 Starting Linux kernel .......................................14
  4.3 hello_world application ....................................16
  4.4 Audio application ...........................................17
    4.4.1 Features of the audio application ..................17
    4.4.2 Starting the audio application ......................17
    4.4.3 Audio latency in loopback mode .....................18
    4.4.4 Running audio application: examples .............19
      4.4.4.1 Playing DTMF ....................................19
      4.4.4.2 Playing in loopback mode .......................19
      4.4.4.3 Playing a full audio pipeline ...............19
      4.4.4.4 Playing an AVB audio pipeline .................21
      4.4.4.5 Playing an SMP full audio pipeline .........38
  4.5 Industrial application ....................................39
    4.5.1 Features of the industrial application ..........40
    4.5.2 Starting the industrial application ..............40
    4.5.3 Running the industrial application: examples ......41
      4.5.3.1 FlexCAN multiple nodes communication .......41
      4.5.3.2 Ethernet through MCUXpresso SDK API ........42
      4.5.3.3 Ethernet with GenAVB/TSN stack ...............44
  4.6 rt_latency application .........................................52
  4.7 Virtio Networking application ..........................55
    4.7.1 Features of the Virtio Networking application ..56
    4.7.2 Running the Virtio Networking application ........56

5 Known Issues .....................................................57

6 Technical Details on Harpoon Applications .............58
  6.1 Description ...................................................58
  6.2 Manual build ................................................58
    6.2.1 Setting up the environment .........................58
    6.2.2 Building the RTOS application for the RTOS cell ....58
      6.2.2.1 Building FreeRTOS based applications ......58
      6.2.2.2 Building Zephyr based applications .......59
    6.2.3 Building the Linux control application for the root cell .............................................59
  6.3 Developing a Harpoon Application ....................60
    6.3.1 Architecture of the audio application ............60
    6.3.2 Source file creation ..................................61
    6.3.3 Board specific code ....................................63
    6.3.4 Controlling application from Linux side ..........63
  6.4 Note About the Source Code in the Document ..........64

8 Revision History ................................................64

9 Legal information ...............................................66

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