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Application Note: AN00218

# High Resolution Delay and Sum

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## Required tools and libraries

The code in this application note is known to work on version 14.2.0 of the xTIMEcomposer tools suite, it may work on other versions.

The application depends on the following libraries:

- lib\_i2s
- lib\_mic\_array\_board\_support
- lib\_mic\_array
- lib\_i2c

## Required hardware

The example code provided with the application has been implemented and tested on the Microphone Array Ref Design v1.

## Prerequisites

- This document assumes familiarity with the XMOS xCORE architecture, the XMOS tool chain and the xC language. Documentation related to these aspects which are not specific to this application note are linked to in the references appendix.
- The lib\_mic\_array user guide should be thoroughly read and understood.
- For a description of XMOS related terms found in this document please see the XMOS Glossary<sup>1</sup>.

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<sup>1</sup><http://www.xmos.com/published/glossary>

# 1 Overview

## 1.1 Introduction

This demo application shows a simple Delay and Sum (DAS) beamformer in high resolution mode. It shows the setup of the I<sup>2</sup>S for audio output via the DAC and very simple processing of multi-channel audio frames to produce a single channel output based on a simple single steering direction.

## 1.2 Block diagram

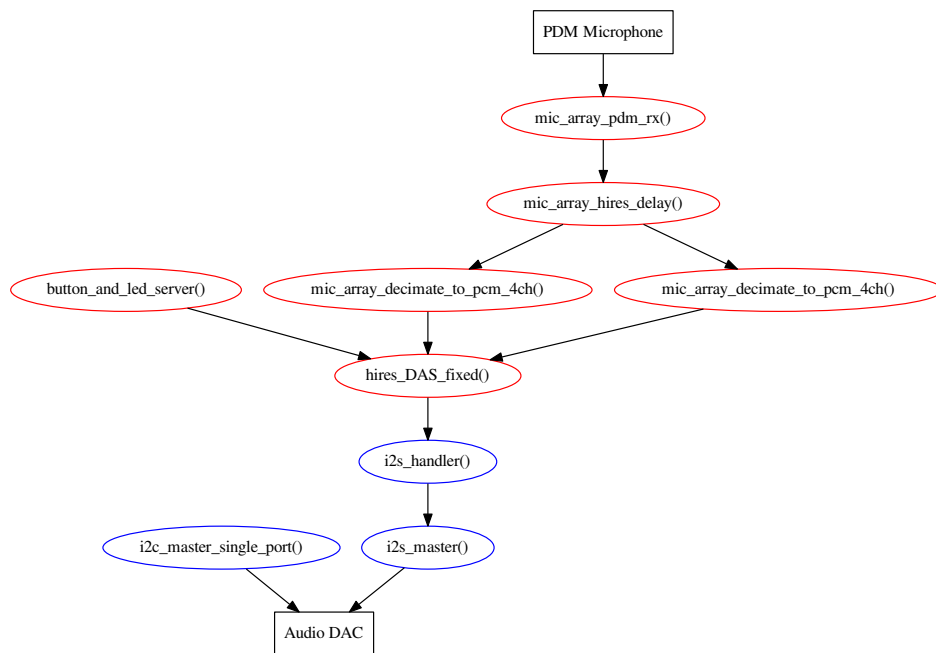


Figure 1: Application block diagram

## 2 How to use lib\_mic\_array with high resolution delay lines

### 2.1 The Makefile

To start using the microphone array library with high resolution delay lines, you need to add `lib_mic_array` to your Makefile:

```
USED_MODULES = .. lib_mic_array ...
```

This demo also uses the logging library (`lib_logging`) for the `debug_printf` function. This is a faster, but more limited version of the C-Standard Library `printf` function. So the Makefile also includes:

```
USED_MODULES = .. lib_logging ..
```

The logging library is configurable at compile-time allowing calls to `debug_printf()` to be easily enabled or disabled. For the prints to be enabled it is necessary to add the following to the compile flags:

```
XCC_FLAGS = .. -DDEBUG_PRINT_ENABLE=1 ..
```

### 2.2 Includes

This application requires the system headers that defines XMOS xCORE specific defines for declaring and initialising hardware:

```
#include <platform.h>
#include <xs1.h>
#include <string.h>
#include <xclib.h>
```

The microphone array library functions are defined in `lib_mic_array.h`. This header must be included in your code to use the library. The support functions for the board are defined in `mic_array_board_support.h` and the logging functions are provided by `debug_print.h`.

```
#include "mic_array.h"
#include "mic_array_board_support.h"
#include "debug_print.h"
```

Also required is support for I<sup>2</sup>S and I<sup>2</sup>C through the headers:

```
#include "i2c.h"
#include "i2s.h"
```

### 2.3 Allocating hardware resources

A PDM microphone requires a clock and a data pin. For eight PDM microphones a single clock can be shared between all microphones and the data can be sampled on a single 8 bit port. On an xCORE the pins are controlled by ports. The application therefore declares one 1-bit port and one 8-bit port:

```
on tile[0]: in port p_mclk           = XS1_PORT_1F;
on tile[0]: clock pdmclk           = XS1_CLKBLK_1;
```

and are configured with:

```
configure_clock_src_divide(pdmc1k, p_mc1k, MASTER_TO_PDM_CLOCK_DIVIDER);
configure_port_clock_output(p_pdm_clk, pdmc1k);
configure_in_port(p_pdm_mics, pdmc1k);
start_clock(pdmc1k);
```

The result begin a 3.072MHz PDM clock is used for clocking the microphone data into the xCORE. Additionally, the leds and buttons are declared by

And the I<sup>2</sup>S is declared with:

```
out buffered port:32 p_i2s_dout[1] = on tile[1]: {XS1_PORT_1P};
in port p_mc1k_in1 = on tile[1]: XS1_PORT_10;
out buffered port:32 p_bclk = on tile[1]: XS1_PORT_1M;
out buffered port:32 p_lrc1k = on tile[1]: XS1_PORT_1N;
port p_i2c = on tile[1]: XS1_PORT_4E; // Bit 0: SCLK, Bit 1: SDA
port p_rst_shared = on tile[1]: XS1_PORT_4F; // Bit 0: DAC_RST_N, Bit 1: ETH_RST_N
clock mc1k = on tile[1]: XS1_CLKBLK_3;
clock bclk = on tile[1]: XS1_CLKBLK_4;
```

### 3 Demo Hardware Setup

To run the demo, connect a USB cable to power the Microphone Array Ref Design v1 and plug the xTAG to the board and connect the xTAG USB cable to your development machine. You will also need to connect headphones to the audio jack.



Figure 2: Hardware setup

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## 4 Launching the demo application

Once the demo example has been built either from the command line using `xmake` or via the build mechanism of `xTIMEcomposer studio` it can be executed on the Microphone Array Ref Design v1.

Once built there will be a `bin/` directory within the project which contains the binary for the xCORE device. The xCORE binary has a XMOS standard `.xe` extension.

### 4.1 Launching from the command line

From the command line you use the `xrun` tool to download and run the code on the xCORE device:

```
xrun --xscope bin/app_hires_DAS_fixed.xe
```

Once this command has executed the application will be running on the Microphone Array Ref Design v1.

### 4.2 Launching from xTIMEcomposer Studio

From `xTIMEcomposer Studio` use the run mechanism to download code to xCORE device. Select the xCORE binary from the `bin/` directory, right click and go to Run Configurations. Double click on xCORE application to create a new run configuration, enable the xSCOPE I/O mode in the dialog box and then select Run.

Once this command has executed the application will be running on the Microphone Array Ref Design v1.

### 4.3 Running the application

Once the application is started using either of the above methods there will be the output of the microphones through the headphones.

Buttons A and D rotate the direction of the beam which is indicated by the LEDs. Buttons B and C decrease and increase the gain on the output signal respectively.

## 5 Task setup

The PDM microphones interface task, high resolution delay task and the decimators have to be connected together and to the application (`hires_DAS_fixed()`). There needs to be one `mic_array_decimate_to_pcm_4ch()` task per four channels that need processing. There needs to be only one `mic_array_hires_delay` task for up to 16 channels. The PDM interface task, `mic_array_pdm_rx()` can process eight channels so only one is needed for this application. The PDM interface needs to be connected to the high resolution interface via two streaming channels and connected to the two decimators via streaming channels. Finally, the decimators have to be connected to the application.

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Note that the decimators have to be on the same tile as the application due to shared frame memory. Also, there needs to be a channel between the `mic_array_hires_delay` and the application in order to issue the commands to change the taps on each delay line.

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## 6 Frame memory

For each decimator a block of memory must be allocated for storing FIR data. The size of the data block must be:

```
Number of channels for that decimator * THIRD_STAGE_COEFS_PER_STAGE * Decimation factor * sizeof(int)
```

bytes. The data must also be double word aligned. For example:

```
int data[8][THIRD_STAGE_COEFS_PER_STAGE*DECIMATION_FACTOR];
```

Note that on the xCORE-200 all global arrays are guaranteed to be double-word aligned.



## 7 Configuration

Configuration of the microphone array for the example is achieved through:

```
mic_array_decimator_conf_common_t dcc = {0, 1, 0, 0, DECIMATION_FACTOR,
    g_third_stage_div_2_fir, 0, FIR_COMPENSATOR_DIV_2,
    DECIMATOR_NO_FRAME_OVERLAP, FRAME_BUFFER_COUNT};
mic_array_decimator_config_t dc[2] = {
    {&dcc, data[0], {INT_MAX, INT_MAX, INT_MAX, INT_MAX}, 4},
    {&dcc, data[4], {INT_MAX, INT_MAX, INT_MAX, INT_MAX}, 4}
};

mic_array_decimator_configure(c_ds_output, DECIMATOR_COUNT, dc);
```

All configuration options are described in the Microphone array library guide. Once configured then the decimators require initialization via:

```
mic_array_init_time_domain_frame(c_ds_output, DECIMATOR_COUNT, buffer, audio, dc);
```

The the decimators will start presenting samples in the form of frames that can be accessed with:

```
mic_array_frame_time_domain * current =
    mic_array_get_next_time_domain_frame(c_ds_output, DECIMATOR_COUNT, buffer, audio, dc);
```

The return value of `mic_array_get_next_time_domain_frame()` is a pointer to the frame that the application is allowed to access. The current frame contains the frame data in the `data` member. `data` is a 2D array with the first index denoting the channel number and the second index denoting the frame index. The frame index used 0 for the oldest samples and increasing indices for newer samples.

## 8 Updating the delays

The high resolution delay task is initially set to delay all channels by a zero 384kHz clock cycles. Each channel can be delayed by up to MIC\_ARRAY\_HIRES\_MAX\_DELAY (default 256) samples at a sample rate of 384kHz. Setting of the taps is done through the function `mic_array_hires_delay_set_taps()`; which will do an atomic update of all the active delay lines tap positions at once.

## 9 Delay taps

The delays on the microphones are calculated in a spread sheet included at the root folder of the application, `mic_array_das_beamformer_calcs.xls`. The beam is focused to a point of one meter away at an angle of thirty degrees from the plane of the microphone array in the direction indicated by the LEDs.

## 10 References

XMOS Tools User Guide

<http://www.xmos.com/published/xtimecomposer-user-guide>

XMOS xCORE Programming Guide

<http://www.xmos.com/published/xmos-programming-guide>

XMOS Microphone Array Library

[http://www.xmos.com/support/libraries/lib\\_mic\\_array](http://www.xmos.com/support/libraries/lib_mic_array)

XMOS I<sup>2</sup>C Library

[http://www.xmos.com/support/libraries/lib\\_i2c](http://www.xmos.com/support/libraries/lib_i2c)

XMOS I<sup>2</sup>S Library

[http://www.xmos.com/support/libraries/lib\\_i2s](http://www.xmos.com/support/libraries/lib_i2s)

## 11 Full source code listing

### 11.1 Source code for app\_hires\_DAS\_fixed.xc

```
// Copyright (c) 2016, XMOS Ltd, All rights reserved
#include <platform.h>
#include <xs1.h>
#include <string.h>
#include <xclib.h>

#include "mic_array.h"
#include "mic_array_board_support.h"
#include "debug_print.h"

#include "i2c.h"
#include "i2s.h"

//If the decimation factor is changed the the coefs array of decimator_config must also be changed.
#define DECIMATION_FACTOR 2 //Corresponds to a 48kHz output sample rate
#define DECIMATOR_COUNT 2 //8 channels requires 2 decimators
#define FRAME_BUFFER_COUNT 2 //The minimum of 2 will suffice for this example

on tile[0]: mabs_led_ports_t leds = MIC_BOARD_SUPPORT_LED_PORTS;
on tile[0]: in port p_buttons = MIC_BOARD_SUPPORT_BUTTON_PORTS;

on tile[0]: out port p_pdm_clk = XS1_PORT_1E;
on tile[0]: in buffered port:32 p_pdm_mics = XS1_PORT_8B;
on tile[0]: in port p_mclk = XS1_PORT_1F;
on tile[0]: clock pdmclk = XS1_CLKBLK_1;

out buffered port:32 p_i2s_dout[1] = on tile[1]: {XS1_PORT_1P};
in port p_mclk_in1 = on tile[1]: XS1_PORT_10;
out buffered port:32 p_bclk = on tile[1]: XS1_PORT_1M;
out buffered port:32 p_lrclk = on tile[1]: XS1_PORT_1N;
port p_i2c = on tile[1]: XS1_PORT_4E; // Bit 0: SCLK, Bit 1: SDA
port p_rst_shared = on tile[1]: XS1_PORT_4F; // Bit 0: DAC_RST_N, Bit 1: ETH_RST_N
clock mclk = on tile[1]: XS1_CLKBLK_3;
clock bclk = on tile[1]: XS1_CLKBLK_4;

// Based on the spreadsheet mic_array_das_beamformer_calcs.xls,
// which can be found in the root directory of this app
static const one_meter_thirty_degrees[6] = {0, 23, 66, 87, 66, 23};

static void set_dir(client interface mabs_led_button_if lb,
                    unsigned dir, unsigned delay[]) {

    for(unsigned i=0; i<MIC_BOARD_SUPPORT_LED_COUNT; i++)
        lb.set_led_brightness(i, 0);
    delay[0] = 43;
    for(unsigned i=0; i<6; i++)
        delay[i+1] = one_meter_thirty_degrees[(i - dir + 3 + 6)%6];

    switch(dir){
    case 0:
        lb.set_led_brightness(0, MIC_BOARD_SUPPORT_MAX_LED_BRIGHTNESS);
        lb.set_led_brightness(1, MIC_BOARD_SUPPORT_MAX_LED_BRIGHTNESS);
        break;
    case 1:
        lb.set_led_brightness(2, MIC_BOARD_SUPPORT_MAX_LED_BRIGHTNESS);
        lb.set_led_brightness(3, MIC_BOARD_SUPPORT_MAX_LED_BRIGHTNESS);
        break;
    case 2:
        lb.set_led_brightness(4, MIC_BOARD_SUPPORT_MAX_LED_BRIGHTNESS);
        lb.set_led_brightness(5, MIC_BOARD_SUPPORT_MAX_LED_BRIGHTNESS);
        break;
    case 3:
        lb.set_led_brightness(6, MIC_BOARD_SUPPORT_MAX_LED_BRIGHTNESS);
        lb.set_led_brightness(7, MIC_BOARD_SUPPORT_MAX_LED_BRIGHTNESS);
        break;
    case 4:
        lb.set_led_brightness(8, MIC_BOARD_SUPPORT_MAX_LED_BRIGHTNESS);
        lb.set_led_brightness(9, MIC_BOARD_SUPPORT_MAX_LED_BRIGHTNESS);
        break;
    }
```

```

    case 5:
        lb.set_led_brightness(10, MIC_BOARD_SUPPORT_MAX_LED_BRIGHTNESS);
        lb.set_led_brightness(11, MIC_BOARD_SUPPORT_MAX_LED_BRIGHTNESS);
        break;
    }
}

int data[8][THIRD_STAGE_COEFS_PER_STAGE*DECIMATION_FACTOR];

void hires_DAS_fixed(streaming chanend c_ds_output[2],
    streaming chanend c_cmd,
    client interface mabs_led_button_if lb, chanend c_audio) {
    unsafe {
        mic_array_frame_time_domain audio[FRAME_BUFFER_COUNT];
        unsigned buffer;
        memset(data, 0, 8*THIRD_STAGE_COEFS_PER_STAGE*DECIMATION_FACTOR*sizeof(int));

        unsigned gain = 8;
        unsigned delay[7];
        unsigned dir = 0;
        set_dir(lb, dir, delay);

        mic_array_decimator_conf_common_t dcc = {0, 1, 0, 0, DECIMATION_FACTOR,
            g_third_stage_div_2_fir, 0, FIR_COMPENSATOR_DIV_2,
            DECIMATOR_NO_FRAME_OVERLAP, FRAME_BUFFER_COUNT};
        mic_array_decimator_config_t dc[2] = {
            {&dcc, data[0], {INT_MAX, INT_MAX, INT_MAX, INT_MAX}, 4},
            {&dcc, data[4], {INT_MAX, INT_MAX, INT_MAX, INT_MAX}, 4}
        };

        mic_array_decimator_configure(c_ds_output, DECIMATOR_COUNT, dc);

        mic_array_init_time_domain_frame(c_ds_output, DECIMATOR_COUNT, buffer, audio, dc);

        while(1) {

            mic_array_frame_time_domain * current =
                mic_array_get_next_time_domain_frame(c_ds_output, DECIMATOR_COUNT, buffer,
                    ↪ audio, dc);

            // light the LED for the current directionion

            int t;
            select {
                case lb.button_event(): {
                    unsigned button;
                    mabs_button_state_t pressed;
                    lb.get_button_event(button, pressed);
                    if (pressed == BUTTON_PRESSED) {
                        switch(button) {
                            case 0:
                                dir--;
                                if(dir == -1)
                                    dir = 5;
                                set_dir(lb, dir, delay);

                                debug_printf("dir %d\n", dir+1);
                                for(unsigned i=0;i<7;i++)
                                    debug_printf("delay[%d] = %d\n", i, delay[i]);
                                debug_printf("\n");

                                mic_array_hires_delay_set_taps(c_cmd, delay, 7);
                                break;

                            case 1:
                                if (gain > 0)
                                    gain--;
                                debug_printf("gain: %d\n", gain);
                                break;

                            case 2:
                                gain++;
                                debug_printf("gain: %d\n", gain);
                                break;
                        }
                    }
                }
            }
        }
    }
}

```

```

        case 3:
            dir++;
            if(dir == 6)
                dir = 0;
            set_dir(lb, dir, delay);

            debug_printf("dir %d\n", dir+1);
            for(unsigned i=0;i<7;i++)
                debug_printf("delay[%d] = %d\n", i, delay[i]);
            debug_printf("\n");

            mic_array_hires_delay_set_taps(c_cmd, delay, 7);
            break;
        }
    }
    break;
}
default:break;
}
int output = 0;
for(unsigned i=0;i<7;i++)
    output += (current->data[i][0]>>3);
output *= gain;

// Update the center LED with a volume indicator
unsigned value = output >> 20;
unsigned magnitude = (value * value) >> 8;
lb.set_led_brightness(12, magnitude);

c_audio <: output;
c_audio <: output;
}
}
}

void init_cs2100(client i2c_master_if i2c){
#define CS2100_DEVICE_CONFIG_1    0x03
#define CS2100_GLOBAL_CONFIG     0x05
#define CS2100_FUNC_CONFIG_1     0x16
#define CS2100_FUNC_CONFIG_2     0x17
i2c.write_reg(0x9c>>1, CS2100_DEVICE_CONFIG_1, 0);
i2c.write_reg(0x9c>>1, CS2100_GLOBAL_CONFIG, 0);
i2c.write_reg(0x9c>>1, CS2100_FUNC_CONFIG_1, 0);
i2c.write_reg(0x9c>>1, CS2100_FUNC_CONFIG_2, 0);
}

#define MASTER_TO_PDM_CLOCK_DIVIDER 4
#define MASTER_CLOCK_FREQUENCY 24576000
#define PDM_CLOCK_FREQUENCY (MASTER_CLOCK_FREQUENCY/(2*MASTER_TO_PDM_CLOCK_DIVIDER))
#define OUTPUT_SAMPLE_RATE (PDM_CLOCK_FREQUENCY/(32*DECIMATION_FACTOR))

[[distributable]]
void i2s_handler(server i2s_callback_if i2s,
                 client i2c_master_if i2c, chanend c_audio) {
    p_rst_shared <: 0xF;

    init_cs2100(i2c);
    i2c_regop_res_t res;
    int i = 0x4A;
    uint8_t data = i2c.read_reg(i, 1, res);

    data = i2c.read_reg(i, 0x02, res);
    data |= 1;
    res = i2c.write_reg(i, 0x02, data); // Power down

    // Setting MCLKDIV2 high if using 24.576MHz.
    data = i2c.read_reg(i, 0x03, res);
    data |= 1;
    res = i2c.write_reg(i, 0x03, data);

    data = 0b01110000;
    res = i2c.write_reg(i, 0x10, data);

    data = i2c.read_reg(i, 0x02, res);
    data &= ~1;

```

```

res = i2c.write_reg(i, 0x02, data); // Power up

while (1) {
  select {
    case i2s.init(i2s_config_t &i2s_config, tdm_config_t &tdm_config):
      i2s_config.mode = I2S_MODE_LEFT_JUSTIFIED;
      i2s_config.mclk_bclk_ratio = (MASTER_CLOCK_FREQUENCY/OUTPUT_SAMPLE_RATE)/64;
      break;

    case i2s.restart_check() -> i2s_restart_t restart:
      restart = I2S_NO_RESTART;
      break;

    case i2s.receive(size_t index, int32_t sample):
      break;

    case i2s.send(size_t index) -> int32_t sample:
      c_audio:> sample;
      break;
  }
}

int main() {

  i2s_callback_if i_i2s;
  i2c_master_if i_i2c[1];
  chan c_audio;
  par {
    on tile[1]: {
      configure_clock_src(mclk, p_mclk_in1);
      start_clock(mclk);
      i2s_master(i_i2s, p_i2s_dout, 1, null, 0, p_bclk, p_lrc1k, bclk, mclk);
    }

    on tile[1]: [[distribute]]i2c_master_single_port(i_i2c, 1, p_i2c, 100, 0, 1, 0);
    on tile[1]: [[distribute]]i2s_handler(i_i2s, i_i2c[0], c_audio);

    on tile[0]: {
      configure_clock_src_divide(pdmc1k, p_mclk, MASTER_TO_PDM_CLOCK_DIVIDER);
      configure_port_clock_output(p_pdm_c1k, pdmc1k);
      configure_in_port(p_pdm_mics, pdmc1k);
      start_clock(pdmc1k);

      streaming chan c_pdm_to_hires[2];
      streaming chan c_hires_to_dec[2];
      streaming chan c_ds_output[2];
      streaming chan c_cmd;

      interface mabs_led_button_if lb[1];

      par {
        mabs_button_and_led_server(lb, 1, leds, p_buttons);

        mic_array_pdm_rx(p_pdm_mics, c_pdm_to_hires[0], c_pdm_to_hires[1]);
        mic_array_hires_delay(c_pdm_to_hires, c_hires_to_dec, 2, c_cmd);
        mic_array_decimate_to_pcm_4ch(c_hires_to_dec[0], c_ds_output[0], MIC_ARRAY_NO_INTERNAL_CHANS);
        mic_array_decimate_to_pcm_4ch(c_hires_to_dec[1], c_ds_output[1], MIC_ARRAY_NO_INTERNAL_CHANS);
        hires_DAS_fixed(c_ds_output, c_cmd, lb[0], c_audio);
      }
      stop_clock(pdmc1k);
    }
  }

  return 0;
}

```



