

HVAC System Controller Front-End Architecture Selection Guide



Brian Dempsey and Joseph Wendt

ABSTRACT

Heating, ventilation, and air conditioning (HVAC) controllers have a wide range of applications, spanning simple valve actuation all the way up to high-level processing for intelligent building management and predictive maintenance. This application note discusses HVAC controller hierarchies, system requirements and examples, and device comparisons for processing, analog-to-digital conversion (ADC), and Ethernet PHY.

Table of Contents

| | |
|--|----|
| 1 Introduction | 2 |
| 2 Subsystems Requirements | 3 |
| 2.1 Processing..... | 3 |
| 2.2 Analog Front-End..... | 5 |
| 2.3 Ethernet..... | 7 |
| 2.4 Application Examples..... | 8 |
| 3 Summary | 11 |
| 4 References | 11 |

List of Figures

| | |
|---|----|
| Figure 1-1. HVAC System Architecture..... | 2 |
| Figure 2-1. Sitara AM62x Architecture..... | 3 |
| Figure 2-2. Sitara AM243x Architecture..... | 4 |
| Figure 2-3. MSPM0G350x Architecture..... | 5 |
| Figure 2-4. SPE Sensing Diagram From Leveraging Single-Pair Ethernet in Building Automation | 8 |
| Figure 2-5. System Controller – Processing Hub Diagram..... | 9 |
| Figure 2-6. System Controller – Interface Hub Diagram..... | 10 |
| Figure 2-7. Unit Controller – Edge Node Diagram..... | 10 |

List of Tables

| | |
|---|---|
| Table 2-1. Comparison of Processing Options..... | 3 |
| Table 2-2. Comparison of ADC Options..... | 6 |
| Table 2-3. Comparison of Integrated 12-Bit ADC Options..... | 6 |

Trademarks

Sitara™ is a trademark of Texas Instruments.
Arm® and Cortex® are registered trademarks of Arm Limited (or its subsidiaries) in the US and/or elsewhere.
Bluetooth Low Energy® is a registered trademark of Bluetooth SIG, Inc.
All trademarks are the property of their respective owners.

1 Introduction

Heating, Ventilation, and Air Conditioning (HVAC) controllers serve as the central nervous system of climate control systems, orchestrating the intricate operation between heating, cooling, and ventilation. HVAC controllers play a pivotal role in maintaining a balance between energy efficiency and occupant comfort, ranging from small residential homes to the expansive environments of large corporate buildings.

These controllers can have many different functions and requirements. A low-level *unit controller* can be used to take an input temperature reading and open or close a vent damper accordingly, while more complex *system controllers* require higher processing power, increased ADC and digital-to-analog converter (DAC) channel count, and numerous communication methods to coordinate HVAC across multiple rooms or even an entire building.

This integration is especially important as new building efficiency standards, like the 2020 Energy Performance of Buildings Directive (EPBD), are putting a larger emphasis on smart energy management than ever before. There's often lots of overlap between possible HVAC configurations, which can be seen in [Figure 1-1](#).

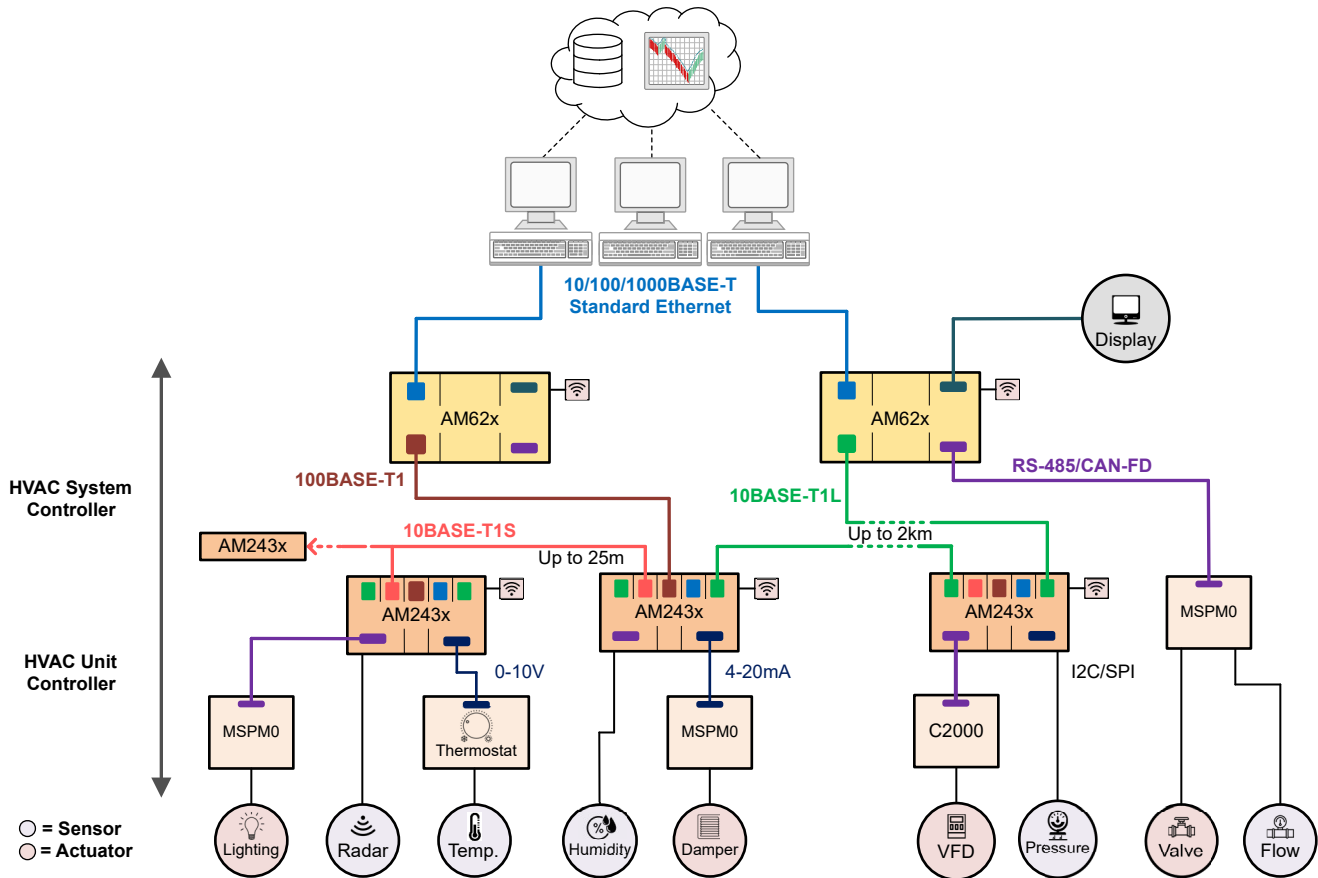


Figure 1-1. HVAC System Architecture

2 Subsystems Requirements

This subsystems section mainly focuses on the selection of processing, analog-to-digital converters (ADC), and Ethernet interface devices. These devices can be mixed-and-matched in many different ways, and examples of this will be shown in [Section 2.4](#).

2.1 Processing

At the heart of the controller there is typically a microprocessor unit (MPU) or microcontroller unit (MCU) depending on the processing capability required. Important specifications when selecting this is processing speed, cores, memory, and functional safety features. This document covers architectures built around three main processing devices: the most capable Sitara AM62x MPU, the peripheral-rich Sitara AM243x MCU, and the most cost-effective MSPM0G350x MCU. For a comparison of these processing options, see [Table 2-1](#).

Table 2-1. Comparison of Processing Options

| | Sitara AM62x MPU | Sitara AM243x MCU | MSPM0G350x MCU |
|---------------------------------|-----------------------------------|-----------------------------------|---|
| Arm Cortex Cores | Quad A53, 1x M4F | 2x Dual R5F, Isolated M4F | M0 w/ MATHACL |
| Operating System | 64 bit | 32 bit | 32 bit |
| Clock Speed | 1400MHz | 800MHz | 80MHz |
| Flash Memory | Up to 8GB external LPDDR4 or DDR4 | Up to 2GB external LPDDR4 or DDR4 | 128KB |
| RAM | 816KB | 2MB | 32kB |
| Ethernet MAC¹ | 2-Port 10/100/1000 | 5-Port 10/100/1000 | --- |
| USB | 2x USB2.0 | 1x USB3.1 DRD | --- |
| CAN-FD | 3x CAN-FD | 2x CAN-FD | 1x CAN-FD |
| Analog Peripherals | --- | 1x 12-bit 4MSPS ADC | 2x 12-bit 4MSPS ADC, DAC, 3x COMP, 3x OPAMP |

1. TSN Compliant Ports

Each MPU or MCU architecture has its own unique power and peripheral requirements, which is shown in [Figure 2-1](#). The analog front-end section has been left as a generic block in these diagrams, and is discussed in more detail in [Section 2.2](#).

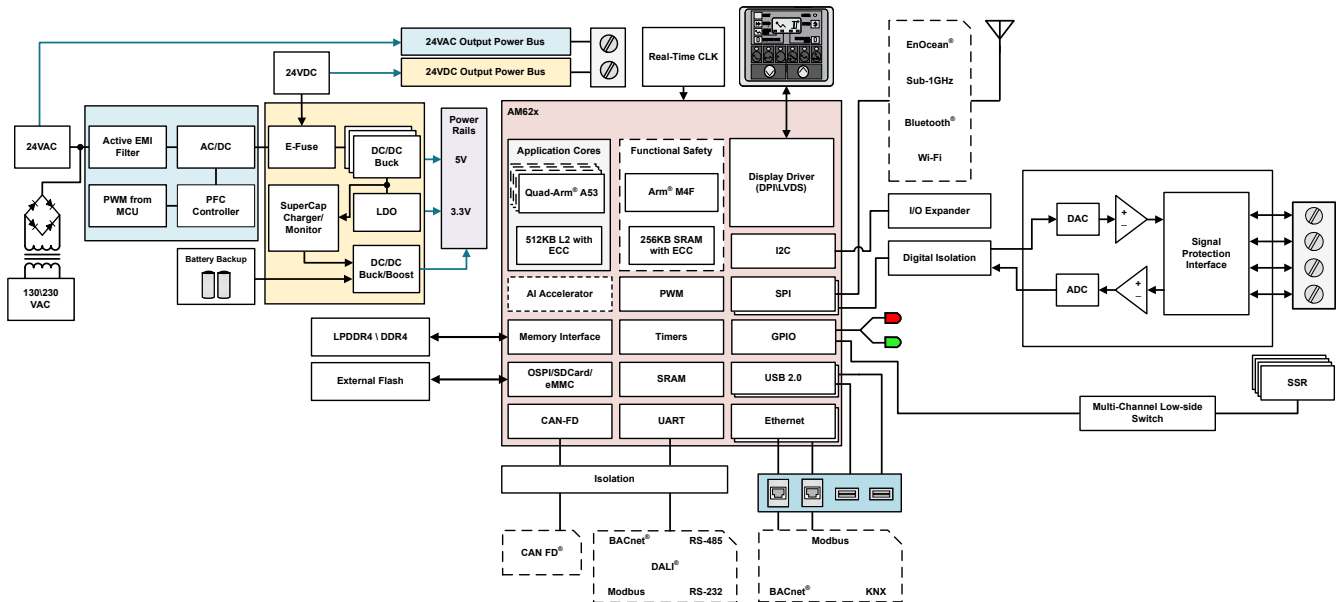


Figure 2-1. Sitara AM62x Architecture

As the only MPU of the three, the Sitara™ AM62x provides the most extensive processing capabilities. The 64-Bit Quadcore Arm® Cortex®-A53 up to 1400MHz and single core Arm Cortex-M4F up to 400MHz manages most HVAC controls and housekeeping tasks with ease, and the built-in 10/100/1000 Ethernet MAC and USB2.0 ports allows high-speed communication across the controller network.

The integrated display driver enables DPI / LVDS communication to an external display, and the memory communication interface allows for up to 8GB of external LPDDR4 or DDR4 memory. The TPS65219 PMIC is selected in the [Powering the AM62x With the TPS65219 PMIC](#) as the best power solution.

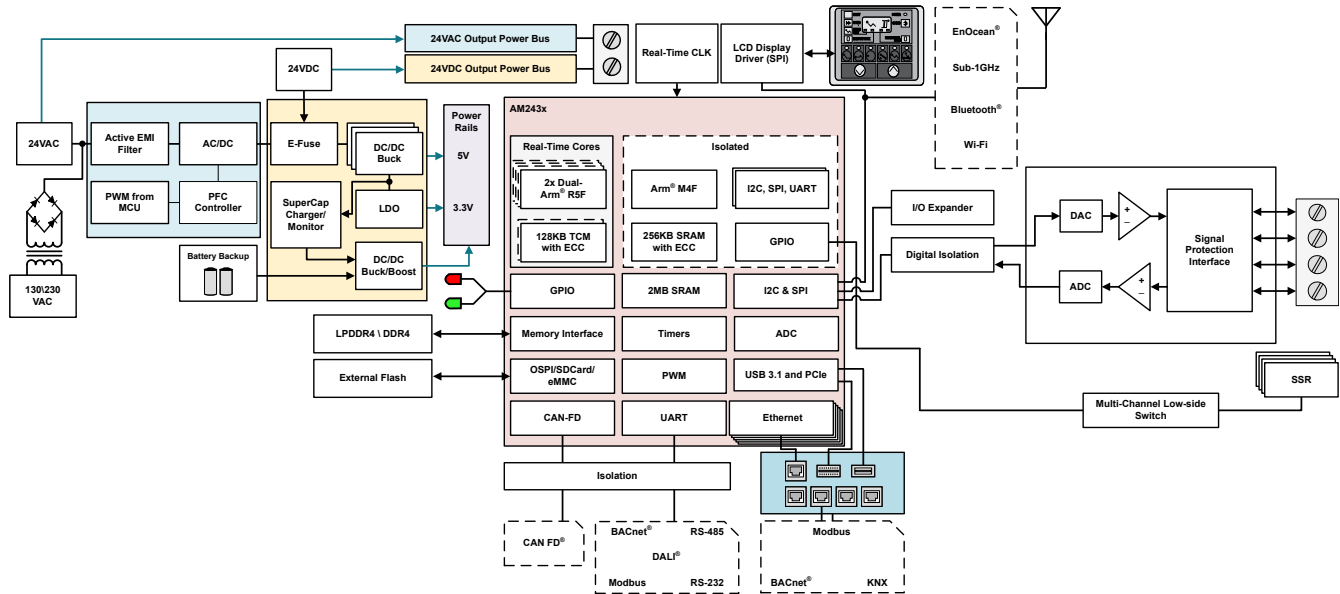


Figure 2-2. Sitara AM243x Architecture

The Sitara AM243x MCU will instead utilize two 800MHz dual-core Arm Cortex-R5F MCU cores and one isolated 400MHz single-core Arm Cortex-M4F MCU for functional safety requirements. It also comes with more capable peripherals such as five Ethernet ports, an updated USB3.1 DRD port, and an integrated 12-bit 4-MSPS ADC supporting up to eight inputs that are internally multiplexed.

The AM243x works well if the full processing power of the AM62x isn't needed, the application requires advanced interface like Ethernet and USB, and the functional safety and ease of use typically found during MCU development is desired. Its two Gigabit Industrial Communication Subsystems (PRU_ICSSG), which enable the five RGMII / RMII / MII Ethernet ports, make it especially capable as an interface hub.

For powering the AM243x, see the [Using LP8733xx and TPS65218xx PMICs to Power AM64x and AM243x Sitara Processors](#), which suggests using the LP87334D PMIC.

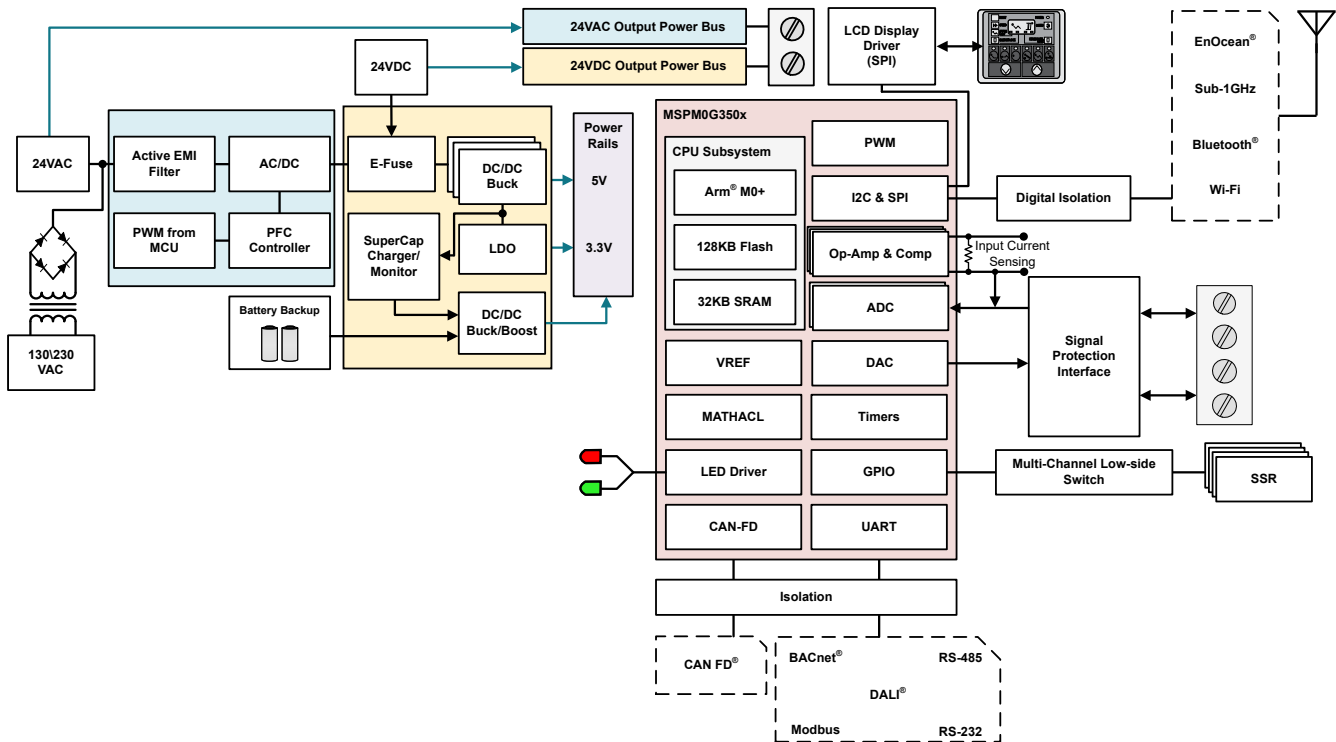


Figure 2-3. MSPM0G350x Architecture

Finally, the most cost-effective option is TI's new MSPM0G350x 80MHz Arm 32-bit Cortex-M0 MCU. This is also going to be the best option for low-power optimized systems, using just 7.6 μ A in max computing RUN mode.

It has a MATHACL computational aide and numerous analog peripherals including two 12-bit 4-MSPS ADCs that can take up to 17 external channels as input, one 12-bit 1-MSPS digital-to-analog converter (DAC) with an integrated output buffer, two zero-drift and zero-crossover op-amps, one general purpose amplifier, and three high speed comparators with 8-bit reference DACs.

These peripherals come with programmable analog connections between them, enabling many different analog configurations, and the ADC also has an adjoining voltage reference, temperature sensor, and supply monitor. For more details on peripherals and the different way to use them, see [Make System Design Easy with MSPM0 Precision Analog](#).

2.2 Analog Front-End

Once the central processing is set by the chosen MPU or MCU, the next key step is deciding how the system will process inputs. There are many technical considerations when selecting ADCs such as input type and range, channel count, single-ended or differential, accuracy, precision, speed, protection, and fault detection. These considerations and the possible analog front-end configurations are discussed in great detail in the [PLC Analog Input Front-End Architectures](#).

In HVAC controllers, the most important specifications tend to be channel count, resolution, and cost. Sample rate is typically not as critical, with many systems only needing ADC sampling speeds of around 1-KSPS.

This application note recommends the four different ADC solutions, as shown in [Table 2-2](#), with two options for 12-bit resolutions, one 16-bit product family, and one 24-bit product family.

Table 2-2. Comparison of ADC Options

| | 12 Bit | | 16 Bit | 24 Bit |
|----------------------------|-----------------------------------|------------------------------|--------------------------------|--------------------------------|
| | Integrated ADC MSPM0C/L/G, AM243x | ADS1015/8 | ADS114S06/6B/8/8B | ADS124S06/8 |
| Input Channels | 8-17 | 4 | 6-12 | 6-12 |
| Architecture | SAR | Delta-Sigma | Delta-Sigma | Delta-Sigma |
| Conversion Rate | 1.5 – 4 MSPS | 3.3 KSPS | 4 KSPS | 4 KSPS |
| Input Type | Differential or Single-Ended | Differential or Single-Ended | Differential or Single-Ended | Differential or Single-Ended |
| PGA | 1-32x | 1-24x | 1-128x | 1-128x |
| Integrated Features | Temp and Supply Sense | VREF, COMP, Temp Sense | 2xiDAC, VREF, Temp Sense, GPIO | 2xiDAC, VREF, Temp Sense, GPIO |
| Interface Type | SPI, I2C, UART, CAN | I2C / SPI | SPI | SPI |

When 12-bit resolution is needed, the most cost-effective solution will be using the integrated ADCs in the MSPM0 or AM243x, even when that means adding an additional MSPM0 in the case of the AM62x. For more information, see the [MSPM0 – ADC Attach on AM62x using SPI](#), which discusses the use of a lower speed MSPM0L ADC for lower price targets. The ADC modules vary between the cost-optimized (MSPM0C), low-power (MSPM0L), and performance-optimized (MSPM0G) lines of the MSPM0, and also the AM243x. For a comparison of the different integrated ADC options between these microcontrollers, see [Table 2-3](#).

Table 2-3. Comparison of Integrated 12-Bit ADC Options

| | MSPM0C | MSPM0L | MSPM0G | AM243x |
|---------------------------|-------------------------------|-----------|-----------------------------|--------|
| ADC Count | 1x | 1x | 2x | 1x |
| External Inputs | 10 | 10 | 17 | 8 |
| Architecture | SAR | SAR | SAR | SAR |
| Conversion Rate | 1.5-MSPS (1.7-MSPS at 10-Bit) | 1.68-MSPS | 4-MSPS (250-KSPS at 14-Bit) | 4-MSPS |
| PGA | --- | 1-32x | 1-32x | --- |
| Analog Peripherals | --- | COMP, OPA | COMP, OPA, DAC | --- |

If higher resolution, better offset and gain error, or off-board placement is needed for the ADC, then one of the discrete analog ADCs would be the better option. The TLA4014 excels at. The ADS114S08/24S08 family is . These devices come in either 6 or 12 channel variations, and share a common package across resolution specifications, making the upgrade from 16 to 24-bit resolution or vice versa a smooth transition if project requirements change.

The MSPM0G has the most capable integrated analog, but all options provide a minimum of 8 external inputs at 12-bits. The MSPM0G can also utilize hardware averaging to achieve a 14-bit resolution at 250-KSPS, which is still a higher sampling rate than is typically needed for HVAC applications.

The PGA feature in the MSPM0L and MSPM0G is found in the form of the integrated op-amps, which utilize the same input pins as the ADC and can output directly to another ADC input pin. This means that for each op-amp input used, there will be one less ADC external input channel available. Also, each op-amp output is internally connected to a specific ADC memory configuration, enabling a PGA to ADC combination for 2 of the 17 available inputs.

If higher resolution, improved offset and gain error, or discrete implementation is needed for the ADC, then one of the discrete analog ADCs would be the better option. Discrete precision ADCs can also be desired for their improved specification drift over time compared to MCU integrated ADCs, which is important in long-term industrial HVAC applications.

The ADS1015 and ADS1018 are ideal 12-bit resolution alternatives to the integrated MCU because of their better performance and integrated PGA that can support all four channels. They come with similar integrated peripherals like an oscillator, voltage reference, temperature sensor, and comparator and their small footprint allows the addition of multiple devices to meet channel count needs.

The ADS114S0x (16-bit resolution) and ADS124S0x (24-bit resolution) families fit well in HVAC controllers requiring higher resolution ADCs. These devices come in either 6 or 12 channel variations, and share a common package across resolution specifications, making the switch between 16-bit and 24-bit resolution options seamless in projects with changing requirements.

This device family has many integrated features which include: 50/60 Hz Rejection, excitation current sources (iDACs) for RTD biasing, 1-128x PGA, oscillator, voltage reference, temperature and power supply sensors, and GPIO pins. There is also the ADS114S06B/8B device line which comes at a lower price for cost-optimized applications. The B devices come with all the same integrated features, but reduced performance. For a detailed breakdown of the performance differences, see [Comparing ADS114S06 and ADS114S08 to the Lower-Cost ADS114S06B and ADS114S08B](#).

2.3 Ethernet

Ethernet is becoming increasingly popular as the communication interface of choice between HVAC controllers. New building efficiency standards are putting a bigger focus on smart energy management protocols and predictive maintenance, and that requires HVAC systems that are more connected than ever before. The high bandwidth enabled by Standard Ethernet, as well as the growing capability of Single Pair Ethernet (SPE) data and power delivery, makes Ethernet ideal for transferring the increasing amounts of data that must be managed in HVAC.

Standard Ethernet has been iterated upon many times, but the most common protocols are:

- IEEE 802.3.i (10 Mbps)
- IEEE 802.3.u (100 Mbps)
- IEEE 802.3.ab (1,000 Mbps)

And SPE is broadly classified into three categories:

- IEEE 802.3.cg (10 Mbps)
- IEEE 802.3.bw (100 Mbps)
- IEEE 802.3.bp (1,000 Mbps)

IEEE 802.3.cg has two more classifications, which define 10BASE-T1L and 10BASE-T1S as well. 10BASE-T1L is long-distance Ethernet and enables point-to-point connections over a single twisted pair at distances up to 2,000 meters. 10BASE-T1S is short-distance Ethernet that enables multi-drop connections at distances up to 25 meters. 10BASE-T1L also adds Power over Data Line (PoDL), also known as Single-Pair Power over Ethernet (SPoE), which reduces solution costs, power loss, and deployment time.

In [Figure 1-1](#), a combination of 10/100/1000 Standard Ethernet, 100BASE-T1, 10BASE-T1L, and 10BASE-T1S protocols is shown. Each control panel board communicating over Ethernet contains external Ethernet PHY(s) and either AM62x or AM243x processors with an integrated Media Access Controller (MAC).

The 10/100/1000 Standard Ethernet will be the most useful in high throughput connections, typically found when communicating to the high-level servers or between system controllers. 10/100/1000 Standard Ethernet is backwards compatible and widely used in existing systems, and 1000BASE-T1 SPE can be used if the reduced wiring and additional features like a Signal Quality Indicator (SQI) and Time Domain Reflectometry (TDR) are desired for a more modern system.

The DP83TG720S from TI is an extremely capable 1000BASE-T1 SPE PHY that supports RGMII and SGMII, and 100BASE-T1 SPE PHYs like the DP83TC813S are available for lower bandwidth requirements. In enterprise level systems requiring 10/100/1000 Standard Ethernet PHYs, the DP83869 PHY supports media conversion between copper and fiber and offers low latency MII, RGMII, and SGMII interfaces and the DP83822 10/100 Standard Ethernet PHY is an ultra-robust option in harsh industrial environments with FX support.

For lower throughput connections, like one to a field sensor or actuator, the 10BASE-T1L and 10BASE-T1S SPE protocols are particularly useful. With the 2km range enabled by 10BASE-T1L, distant field nodes can transmit and receive high fidelity data that further enables intelligent management by the central controller. The multidrop functionality found in 10BASE-T1S is ideal for very short distance connections between many different controllers or boards, as is often found in HVAC control cabinets, or to support multiple end nodes on the same bus.

The DP83TD510E 10BASE-T1L PHY can enable the T1L connection at 2km, and is ultra-low power to help meet energy efficiency requirements. Contact TI for more information about 10BASE-T1S products. For more information on the benefits, applications, and devices found in Single Pair Ethernet, see [Leveraging Single-Pair Ethernet in Building Automation](#).

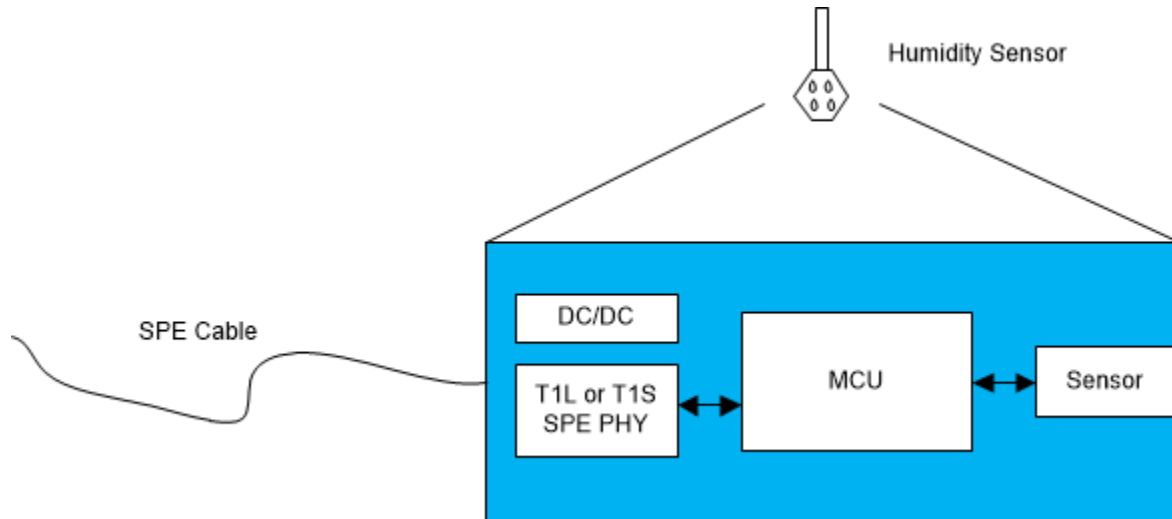


Figure 2-4. SPE Sensing Diagram From Leveraging Single-Pair Ethernet in Building Automation

In this HVAC controller application example found in the application note, SPE sensing is shown with just one connection to the system. The SPE provides both full duplex data transfer and power delivery, so the entire sensing board can be achieved with just a 10BASE-T1L or 10BASE-T1S PHY, DC to DC conversion using the power provided by the data line, an Ethernet MAC enabled MCU such as the AM243x, and the sensor or sensors of choice.

2.4 Application Examples

HVAC controller functionality generally falls into a few common categories. In the following section, three example systems derived from [Figure 2-5](#) are shown: system controller – processing hub, system controller – interface hub, and unit controller – edge node. The devices in these diagrams were selected to meet performance and channel-count requirements while optimizing for the low cost that is typically desired in building automation markets.

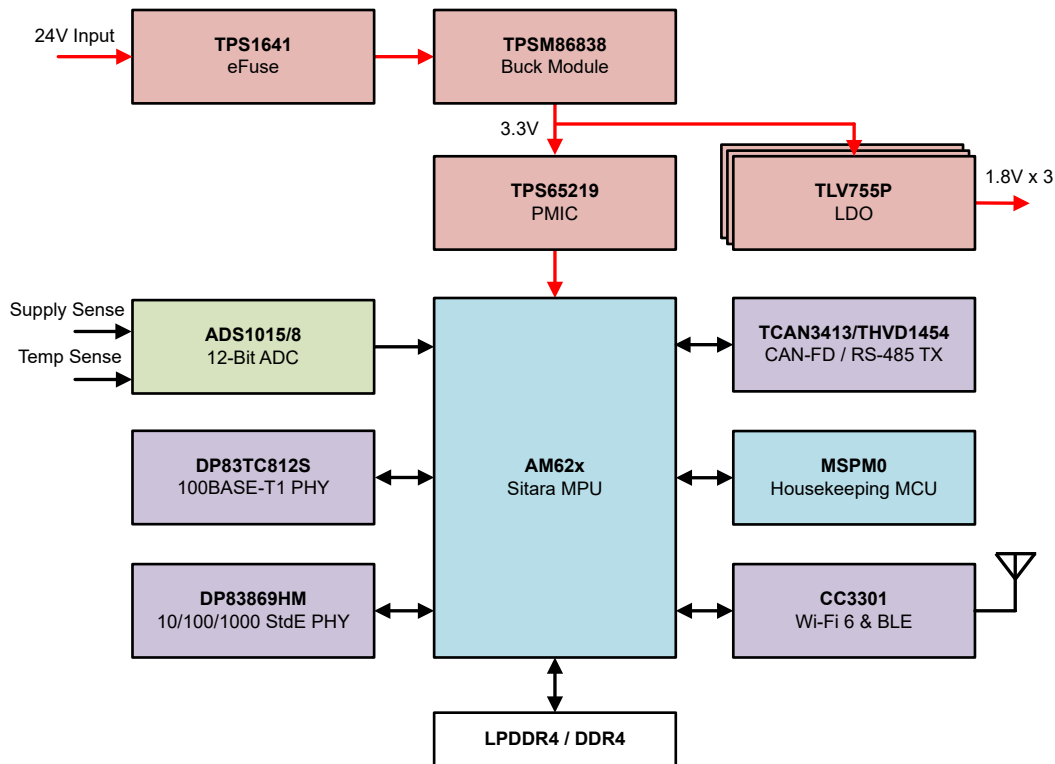


Figure 2-5. System Controller – Processing Hub Diagram

The top-level system controller needs the highest processing capability, high speed interface, and minimal analog hardware. The board will typically be found in accessible control panels, where the building’s HVAC systems are managed and supported. It’s very common for a modular I/O board to be nearby, accompanying this processing-focused controller.

Ethernet is usually the best way to communicate between these controllers and their surroundings, and that can be accompanied by wireless connectivity over Wi-Fi 6 and Bluetooth Low Energy® (BLE) to stay connected with broader IT networks. As for the analog hardware, an ADC likely won’t be needed for sensing at this level, but could be warranted if supply power and ambient temperature must be monitored to meet reliability and safety requirements.

For the power tree, a 24V DC input goes to an eFuse protection device providing 15W power limiting to meet the IEC60335 and UL60730 safety standards. A buck step-down module with an integrated switch and inductor then converts the 24V to 3.3V DC output. The Sitara MPU can be powered by the TPS65219 PMIC and a discrete LDO, and additional LDOs can be added for powering external memory and connectivity peripherals.

The [AM62x Power Estimation Tool](#) and [AM62x Maximum Current Ratings](#) resources provide guidance when designing estimating power consumption and setting power supply requirements, and the [WEBENCH Power Designer](#) helps find the best power conversion solution for your system’s needs.

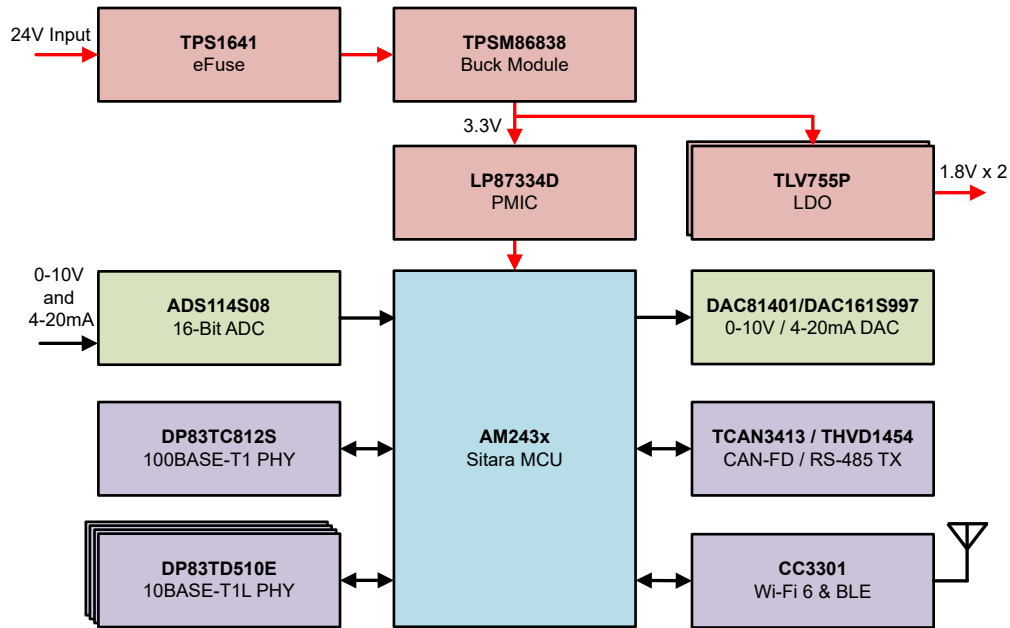


Figure 2-6. System Controller – Interface Hub Diagram

The mid-level system-controller is often integral to connecting the HVAC network. This requires high channel-counts for different interface types, analog-to-digital and digital-to-analog conversion to communicate over legacy 0-10V and 4-20mA lines, and optional wireless connectivity like Wi-Fi and BLE.

The 16-bit ADCs and DACs will enable high fidelity legacy communication, but might not be needed for much edge sensing at this interface-focused level. If DAC performance is not critical, the internal PWM timers in the AM243x combined with external filtering can be used to produce analog outputs. For the other types of interface, the AM243x can support up to 5 Ethernet channels, as well as the common CAN-FD and RS-485 interfaces.

The power tree is similar to the AM62x Sitara MPU, as there is once again an eFuse with 15W power limiting, a buck step-down power module, and a PMIC with accompanying LDOs that power the AM243x and CC3301 connectivity device. Refer to the [AM243x Power Estimation Tool](#) for calculating MCU power consumption.

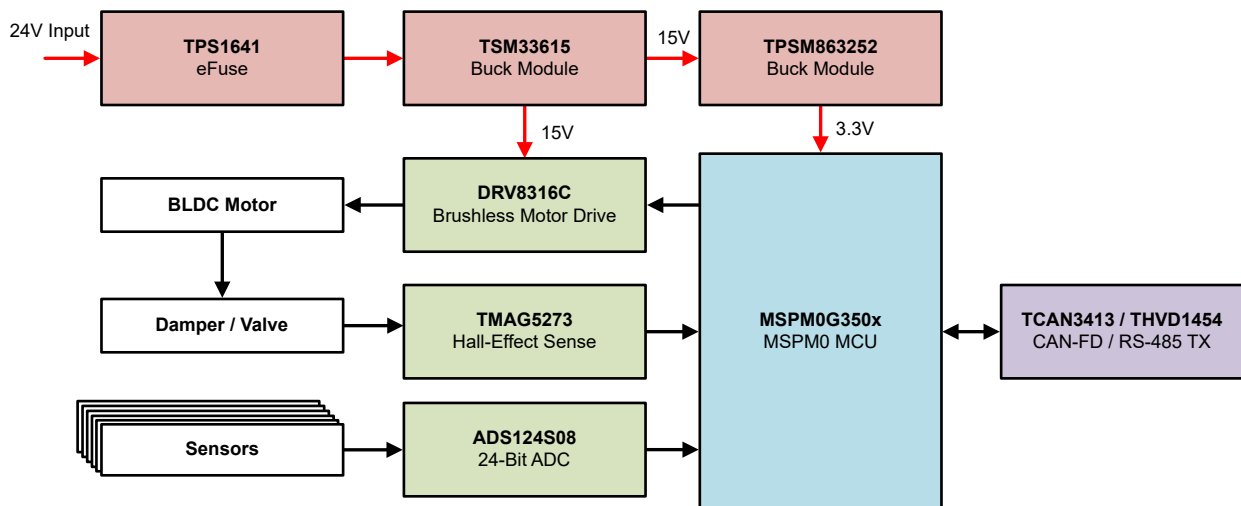


Figure 2-7. Unit Controller – Edge Node Diagram

The edge node unit controller will be the most analog focused, with its main purpose being to conduct all sensing, convert those inputs to useful data communicated to higher level controllers, and actuate mechanisms like a damper or valve based on that data. Large buildings will usually house many of these unit controllers, and as a result they must ride a line between excellent sensing and actuation performance and low-cost, which the MSPM0 excels at.

High ADC channel counts are usually a top careabout, and the resolution requirements are also trending upward. For interface, the MSPM0 can communicate over both CAN-FD or RS-485 with the corresponding transceiver device, and has an integrated 12-bit DAC for 0-10V or 4-20mA data lines.

The power tree is much simpler for the MSPM0, as it can use a more versatile buck step-down module instead of needing a dedicated PMIC. The eFuse power limit of up to 64W, so it can be adjusted to meet the increased current demands of the motor or can be placed after the buck module has converted the supply voltage down to 15V.

3 Summary

HVAC controllers are becoming increasingly common and intelligent with the rise of energy efficiency standards and predictive maintenance needs. These system and unit controllers manage a delicate building hierarchy, and can have many different functions. Texas Instruments is uniquely positioned to provide the best system solution across these applications, and this application note focused on the best combinations of processors, ADCs, and Ethernet PHYs that make up those systems.

4 References

- Texas Instruments: [Powering the AM62x With the TPS65219 PMIC](#)
- Texas Instruments: [Using LP8733xx and TPS65218xx PMICs to Power AM64x and AM243x Sitara Processors](#)
- Texas Instruments: [Make System Design Easy with MSPM0 Precision Analog](#)
- Texas Instruments: [Comparing ADS114S06 and ADS114S08 to the Lower-Cost ADS114S06B and ADS114S08B](#)
- Texas Instruments: [Leveraging Single-Pair Ethernet in Building Automation](#)

IMPORTANT NOTICE AND DISCLAIMER

TI PROVIDES TECHNICAL AND RELIABILITY DATA (INCLUDING DATA SHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES "AS IS" AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS AND IMPLIED, INCLUDING WITHOUT LIMITATION ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for skilled developers designing with TI products. You are solely responsible for (1) selecting the appropriate TI products for your application, (2) designing, validating and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, regulatory or other requirements.

These resources are subject to change without notice. TI grants you permission to use these resources only for development of an application that uses the TI products described in the resource. Other reproduction and display of these resources is prohibited. No license is granted to any other TI intellectual property right or to any third party intellectual property right. TI disclaims responsibility for, and you will fully indemnify TI and its representatives against, any claims, damages, costs, losses, and liabilities arising out of your use of these resources.

TI's products are provided subject to [TI's Terms of Sale](#) or other applicable terms available either on [ti.com](https://www.ti.com) or provided in conjunction with such TI products. TI's provision of these resources does not expand or otherwise alter TI's applicable warranties or warranty disclaimers for TI products.

TI objects to and rejects any additional or different terms you may have proposed.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2024, Texas Instruments Incorporated