Lattice RISC-V Based 5G IIoT Hub

Sponsored by Lattice Semiconductor Corporation | Project Proposal

Acknowledgement

This document was developed by the capstone team, in alignment with provided project proposal expectations and has been further refined through reviews provided by industry sponsor.

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2/2/2024	2/2/2024	2/2/2024

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Table of Contents

1. Executive Summary

This project is oriented onwards ECE 412 capstone at Maseeh College of Engineering and Computer Science, with sponsorship from Lattice Semiconductor Corporation for engineering applications purposes. The deliverables of the project are focused on developing a 5G Industrial Internet of Things (IIoT) Hub using Certus-NX Versa Evaluation Board and RISC-V based System on Chip (SoC). The project's goal is to integrate advanced 5G communications with FPGAs flexibility and performance to control a Brushless DC (BLDC) motor for industrial applications. By connecting to remote servers or cloud services, the 5G module will enable real-time data processing and decision-making. Our final deliverables will include a fully functional prototype, comprehensive documentation, a user manual, and a detailed bill of materials.

2. Background

This project is an FPGA-based IoT application sponsored by Lattice Semiconductor. Lattice is a company that targets the FPGA market, and they usually focus on FPGA-based industrial control. Lattice is perceived as a leader in the FPGA market. It's the last big company standing on its own, because most of the other companies such as Altera and Xilinx have been acquired by other huge companies such as Intel and AMD. The Lattice engineer who is taking control of the project is Rahul Koche. He is part of the applications engineering group.

There have been some other previous variations of this project where the motor was controlled by a Lattice FPGA, and they had direct MQTT traffic going to the FPGA, but 5G was never used in that project. The following picture shows the project that was done at lattice previously.

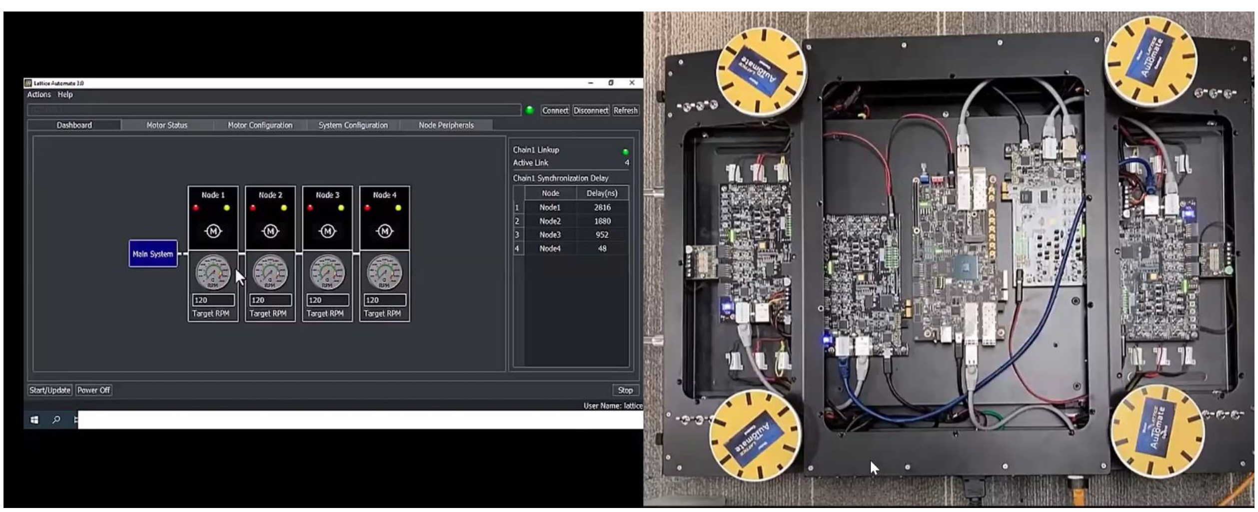


Figure 0: similar project that was completed at Lattice that does motor control

The left of the figure shows an application running on the host PC which is connected to the FPGA via Ethernet cable. Lattice also had an Automate solution using MQTT communication. Specifically, an FPGA was connected to a RaspberryPi via UART which allowed the RaspberryPi and PC to communicate over MQTT. The difference from this previous version and our current project is the 5G modem which will allow direct communication between the PC and FPGA via MQTT.

3. Research

5G wireless communication

5G wireless communication is the fifth generation of cellular communication. Key features of 5G include transmission speeds, reduced latency, and the ability to connect a large number of devices simultaneously. 5G networks offer much higher download speeds compared to 4G, at its peak the speeds can reach 10 gigabits per second. 5G achieves these speeds partly by utilizing higher-frequency radio waves in addition to the frequencies used by previous cellular networks.

Another notable advantage between 5G and 4G is the level of latency. Latency refers to the delay between sending and receiving information. 5G networks have significantly lower latency compared to 4G, which is crucial for applications that require real-time responses, such as remote surgery or in this specific case brushless motor control.

5G networks also operate using a range of frequency bands - low, medium, and high each with its characteristics and applications. Low-band 5G uses frequencies similar to 4G, offering improved speeds and coverage. Mid-band 5G provides faster speeds and lower latency over a wider area, while high-band 5G offers the highest speeds and lowest latency but has limited range. In our case we will most likely be focussed on that high-band communication for our task at hand.

Due to all the features introduced there are many new use cases that were previously not possible. Some of these being high-quality video streaming, effective communication among IoT devices, as well as more accurate location tracking. 5G also supports network slicing, allowing the creation of multiple virtual networks within a single physical 5G network to support specific uses or business cases. 5G's potential to support a broad range of industries and applications is expected to have a significant impact on economies of scale. Various industries are poised to benefit from the deployment of 5G. These include healthcare, manufacturing, retail, media and entertainment, and transportation. 5G technology is integral to enable and enhance technologies like AI, machine learning, industrial robotics, and smart city infrastructures.

Open Source Projects

Our team will utilize an open-source MQTT client library from GitHub, ensuring it aligns with Lattice Semiconductor's IP requirements and the library's open-source license for effective communication in our 5G IIoT Hub.

Commercial Off-the-Shelf Products

We are considering the BG96BRDR22 5G module (DigiKey Part Number 3082-BG96BRDR22-ND), for connectivity. Its compatibility with Lattice FPGA boards and project requirements will be evaluated in consultation with our industry sponsor.

Patens, Papers, White Papers, Articles, Conference Proceedings

Key literature, like Hossam Fattah's "LTE Cellular Narrowband Internet of Things (NB-IoT): Practical Projects for the Cloud and Data Visualization," is being reviewed for insights into LTE and NB-IoT applications, relevant to our project's data handling and cloud integration.

4. Product Design Specification

4.1. Product Overview

The service involves a cell modem that receives instructions from a cellular device which is then relayed to the FPGA (RISC-V based) board. Then the board will use these instructions as commands for controlling the brushless DC motor. Lattice wants to demonstrate this product at conventions; for that to be possible our team needs to provide Lattice with a detailed user's manual so they can show the capabilities. As of right now we do not have a lifespan goal for this product, but in general it should last as long as its individual components. Also, the product is modular so there is room for component replacements if one does reach its end of life. This project will be successful if Lattice will have a working IIoT 5G modem that meets their expectations.

4.2. Stakeholders

In our 5G IIoT Hub project, Lattice Semiconductor, specifically their Application Engineering team, is the primary stakeholder. They will guide the project, providing resources for its development and potentially leveraging the final product for application purposes and demonstrations at conferences. Our development team and the end-users are also crucial stakeholders, influencing the project's design and functionality to ensure its success in real-world applications and presentations.

4.3. Requirements

The following requirements are specified to ensure that the project meets user needs, industry standards, and technological efficacy for robust IIoT applications. This section details the core outlines encompassing system integration, communication, motor control, software programming, and user experience:

Hardware:

- Must use an existing Lattice development board.
- Must integrate with an off-the-shelf 5G modem, capable of connecting to a host PC.
- Must be able to communicate with and control the motor with the board which receives instructions from the modem.
- Must have the capability to manage actuator configuration, monitoring, or control from a cloud or remote server.

Software:

- Must include software or applications for efficient sensor data collection and management.
- Must have programs that are used to interface each module.

Quality:

- Must be well documented and user-friendly.
- Must be neatly assembled without any exposed wires or hardware.
- Must ensure durability and safety in industrial environments.
- Must perform reliably under typical industrial conditions and IoT industry standards.
- Must ensure rapid response time for real-time control and data management.

4.4. Specifications

Hardware:

- Specific board is the Lattice Certus-NX Versa Evaluation Board
- Specific modem: BG96BRDR22 5G module | RF and Wireless | DigiKey Marketplace
- Must use UART as the serial interface between the 5G IIoT modem and the Industrial Automation Framework. This will facilitate communication between the 5G modem and Lattice FPGA.
- Must control a BLDC motor using PMOD connectors.

Software:

- Must run a RISC-V SoC for controlling UART and FPGA peripherals.
- Must use MQTT as the transport protocol between the Cloud and the 5G IIoT modem. (See Appendix A).
- Any custom hardware should be ideally written with Verilog.
- Programming will likely be done in C++ for software development.

Service:

- Must use Amazon Web Service: This is the Cloud, which is used to monitor, control, configure, and execute Industry 4.0 platform. (See Appendix B).
    - A backup to this service is the MQTT protocol.

4.5. Deliverables

Capstone Advisor:

- A project proposal.
- Weekly progress reports, which break down the tasks done that week by the team and individual members, as well as any roadblocks encountered.
- Final project presentation to faculty advisor and industry sponsor.
- A final report with an ECE poster for ECE capstone poster session.

Industry Sponsor:

- A working 5G industrial IoT hub that can control the actuators and collect sensor data (neatly delivered without flying wires or hardware exposed).
- RTL/firmware source code that was created as well as any associated apps or software that is in charge of collecting sensor data.
- A user guide.
- A bill of materials.

4.6. Initial product design

4.6.1. Existing System

Current IIoT solutions do not fully exploit the potential of 5G in conjunction with FPGA technologies, particularly in the realm of industrial applications. Our project builds upon the existing capabilities of Lattice's FPGA boards and aims to integrate them with 5G technology for enhanced industrial IoT applications.

4.6.2. Proposed Product Design

We propose a system that leverages the Lattice FPGA's capabilities to communicate with a 5G modem over UART, controlling a BLDC motor and managing industrial sensors/actuators. This design must be user-friendly, efficient, and adhere to industry standards.

4.6.3. Hardware architecture

Figure 1 below represents the Level 0 diagram and provides a simplified overview of the 5G IIoT Hub system, showing key inputs like power, user commands, and sensor data, alongside essential outputs such as actuator signals and user feedback.

Figure 1: L0 - Block diagram

Whereas the L1 diagram in *figure 2* builds on the L0 foundation, detailing the system's internal structure. It breaks down the main components, such as the power supply, FPGA, 5G module, and illustrates their interconnections and the flow of data within the system.

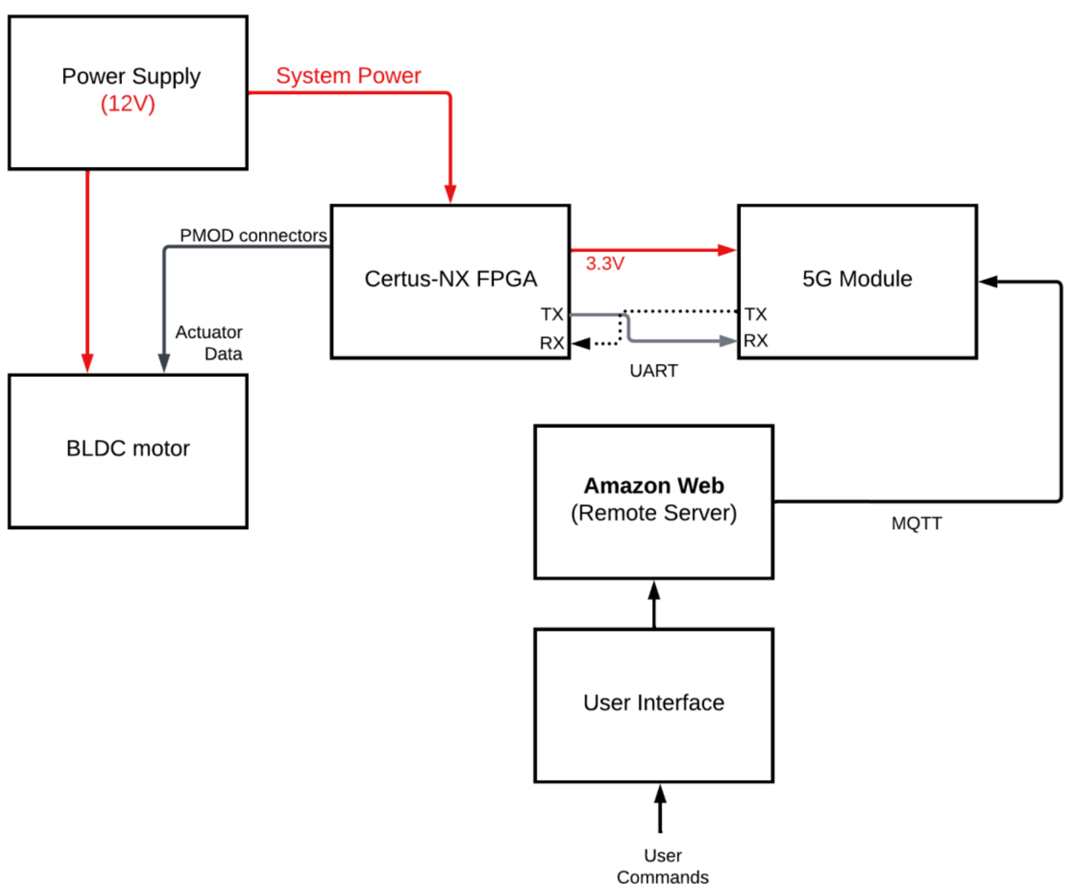


Figure 1: L1 - Block diagram

Pending a detailed high-level framework from Lattice, in the next version of the proposal, a more detailed Level 2 (L2) diagram will be provided. It will feature in-depth sub-interconnections within the system, including:

- Specific Actuator and Motor Control sub-types and controls.
- FPGA internals like the Core RISC-V SoC and peripheral controllers.
- 5G module components such as the antenna system.
- Expanded Remote Server architecture showing databases and services.
- Labeled Communication Protocols to clarify data exchanges.
- A defined User Interface block with display and input specifics.
- Detailed Interconnects and types, including PMOD connector specifications.
- Integration points for External Systems such as PLCs or SCADA.

4.6.4. Software architecture

Our software architecture utilizes **Lattice Radiant** for design optimization and **Lattice Propel** for system integration, with **SystemVerilog** for hardware description. For visual design and project management, **Lucidchart** will be employed to create clear block diagrams and project schedules.

4.6.5. User interface

End-users will interact with the 5G module through a web based interface, for displaying collected sensor data and input commands to control actuators and receive processed data. Additionally, a user guide will be provided to ensure full access to product datasheets and technical details.

4.6.6. Other considerations

As part of our goals, the project will ensure secure communication, MQTT traffic is encrypted , by adding an extra layer of security on the User interface to prevent motor control from an unauthorized person. Furthermore, our design regulatory compliance meets industrial IoT standards and the best practices, given the amount of resources provided by Lattice. If we are unable to use amazon web services, then we will use HiveMQ.

4.6.7. Back up plans

Overall, deliverables are well-defined, which ensures that errors and delays are not anticipated. The project will be monitored closely at all times, and if any technical challenges start to arise, we can adjust the project schedule accordingly with a priority of not impacting system functionality and deliveries. If more resources are needed to overcome a specific technical challenge, for example, modem compatibility, the team will look for another off shelf modem and ask for guidance from the faculty advisor and the industry sponsor.

4.7. Verification plans

4.7.1. Cell Interfacing:

When the cell modem receives data, the data should be accurate without any error. This test will be considered a failure if the modem receives inaccurate data.

- Show that the UART interface transmits and receives data correctly by creating a simple program (i.e. turn an LED On)
- Show that the 5G module is receiving data correctly between itself and AWS by creating a simple program to transfer some value to the 5G module (make sure to establish a connection correctly)

4.7.2. SoC of FPGA:

The board should be able to control all FPGA peripherals along with the UART.

- Show that FPGA is receiving correct signals from the UART interface by creating a simple program that takes data from the UART and stores it in memory. Then, in the tool, we will open up memory addresses and check if the data is correct or not.
- Show that the FPGA is sending data correctly on the PMOD connectors by hooking up the connectors with wires and then the wires are hooked up to an oscilloscope

4.7.3. Brushless DC Motor:

The BLDC motor should be able to receive a command and perform the correct function. It will be a critical failure if the motor is performing a function that does not match the instruction, or it is not able to receive commands from the board.

- Show that the BLDC is working by creating a simple program that sends instructions down the PMOD connectors. Then, we will check the motor's reaction. Does the motor and the program's reactions match or not ? (It is considered a failure if I instruct the BLDC to turn clockwise for example ,and then it does not move at all)

4.7.4. Integration of Components:

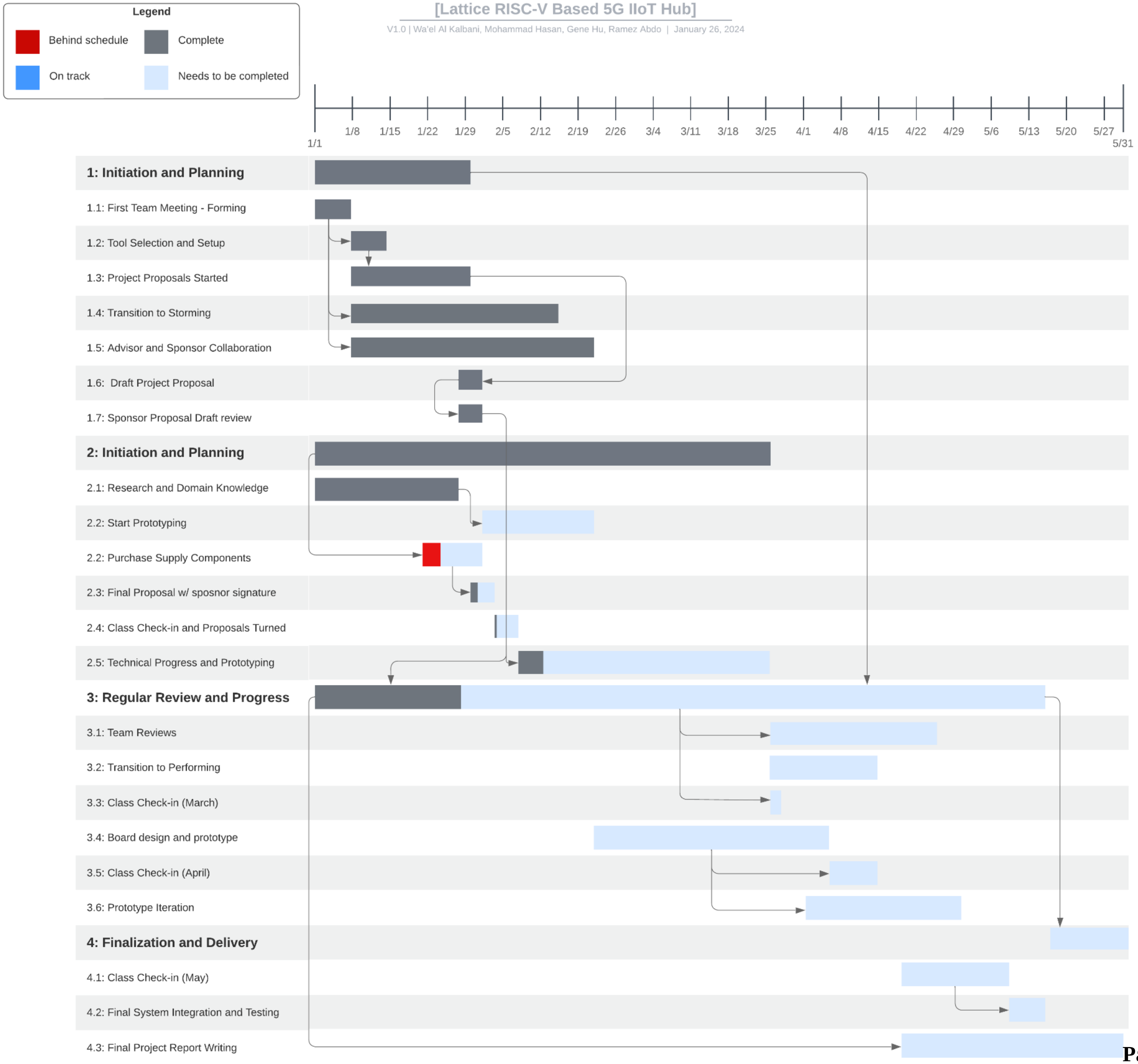
The individual modules should be able to become one device. The cell modem will receive an instruction and relay it to the FPGA board which will then give the motor its command to act upon. Integration will have failed if one part of the chain is broken and the components down the line are unable to act correctly.

- Show that the commands sent by the user interface match the reaction of the BLDC or not.

5. Project Management Plan

5.1. Timeline, with milestones

The project schedule (Gantt chart) - *see next page* - outlines a timeline for our project, considering the complexity and part-time nature of our work. It's designed to accommodate potential delays in procuring materials and unexpected challenges, ensuring flexibility. Key milestones include research completion, initial design, prototyping, and final integration. The Primary tool used to track progress on schedule is lucidchart.


Legend
Behind schedule
Complete
On track
Needs to be completed
[Lattice RISC-V Based 5G IIoT Hub]
V1.0 | Wa'el Al Kalbani, Mohammad Hasan, Gene Hu, Ramez Abdo | January 26, 2024
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4/22
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1: Initiation and Planning
1.1: First Team Meeting - Forming
1.2: Tool Selection and Setup
1.3: Project Proposals Started
1.4: Transition to Storming
1.5: Advisor and Sponsor Collaboration
1.6: Draft Project Proposal
1.7: Sponsor Proposal Draft review
2: Initiation and Planning
2.1: Research and Domain Knowledge
2.2: Start Prototyping
2.2: Purchase Supply Components
2.3: Final Proposal w/ sposnor signature
2.4: Class Check-in and Proposals Turned
2.5: Technical Progress and Prototyping
3: Regular Review and Progress
3.1: Team Reviews
3.2: Transition to Performing
3.3: Class Check-in (March)
3.4: Board design and prototype
3.5: Class Check-in (April)
3.6: Prototype Iteration
4: Finalization and Delivery
4.1: Class Check-in (May)
4.2: Final System Integration and Testing
4.3: Final Project Report Writing

5.2. Budget and Resources

Most of the important components of the projects will be provided by the sponsor. The components include lattice certus-nx boards, 5G module, and the brushless DC motor that we will control. For us as a team, we will be providing the breadboards, wires, LEDs, and small circuitry components such as resistors, capacitors and inductors. All of these components need to be available **as soon as possible**. That way we, as a team, are able to make progress as soon as possible.

The resources that we need from the sponsors are licenses to use the lattice software, hardware components (certus-nx, 5G module and motor) and datasheets for the components. The most important resources that we will provide are access to some facilities including the EPL and the capstone lab. The capstone lab will be mainly the facility that we will use to create, assemble and test the project. We will also provide a locker that will be specialized for keeping all the project components inside.

5.3. Intellectual Property Discussion

Lattice Semiconductor retains ownership of all intellectual property (IP) associated with this project. Our team will utilize existing Lattice IP modules, accessible through an academic license provided by Lattice. Any new IP developed over the course of this project will be the property of Lattice Applications Engineering.

5.4. Team and development process

- ***Team members skills:***
  - Ramez
    - Technical Documentation, C, Python, C++, Linux, Assembly, Circuit analysis
  - Gene
    - C, Python, Verilog
  - Wa’el
    - C/ C++, ARM Assembly, Verilog KiCad
  - Mohammed
    - C/C++, python, PostgreSQL, ARM assembly, RiscV assembly, Verilog, Linux OS

- ***Responsibilities:***
  - Ramez
    - Technical documentation
    - Hardware and software involvement

- Gene
    - Communication point person
    - Technical documentation
- Wa'el
    - Interface with cell
    - Project overall management
    - Help with system on chip of fpga where needed
- Mohammed
    - Hardware and software involvement

- ***Point person of communication:***
    - Gene will be the contact person for both the industry sponsor and faculty advisor.

- ***Team leader:***
    - Wa'el is the team leader, he will head most meetings and ensure all tasks are being completed on time.

- ***Collaboration tools:***
    - We will be using three collaboration tools for documentation. It will be google drive where all of our documents will be stored in a shared drive. For all technical work such as code or schematics we will be using a Github repo. Lastly for all communication such as weekly sprints and updates we communicate through a discord server.

- ***Technical tools:***
    - We will be using Lattice softwares to develop our work.

- ***Methodology:***
    - We will be following the Agile methodology by breaking down the project into phases and continuously improving upon previous phases.

Appendix A

Message Queue Telemetry Transport (MQTT)

NB-IoT devices require a special application-layer protocol suitable for efficient data-transfer to transmit and receive their data. The widely used application-layer protocol is the Message Queue Telemetry Transport (MQTT).

MQTT is an application-layer transport protocol that runs on top of the TCP/IP protocols. MQTT is suitable for NB-IoT devices that have small memory and processing power, are battery-powered, or have scarce bandwidth. MQTT is a lightweight and simple messaging protocol that is best suited for NB-IoT devices and MTC.

MQTT uses a publish/subscribe model to communicate between a transmitter and receiver. In this model, one-to-many distribution is provided. Transmitting applications or devices do not need to know anything about the receiver, not even the destination address. Receiver, on the other hand, does not need to know about the transmitter as well. The publish/subscribe mode is illustrated in Figure 1. In the figure, a single device publishes its data to the server while other devices may subscribe to the server to receive such data from the publisher.

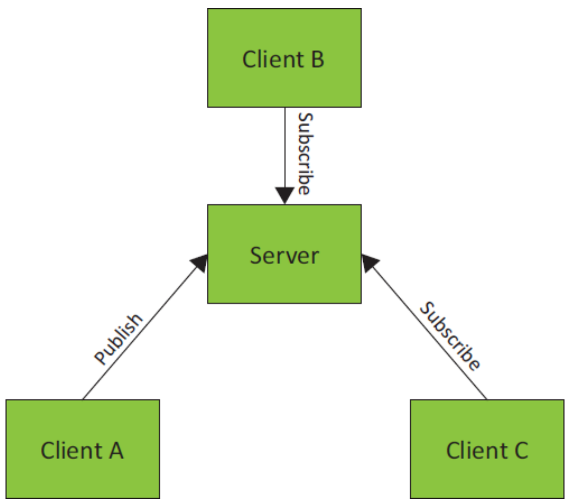

Figure 1: MQTT Client and Server.

NB-IoT device publishes its messages, through the eNodeB, to the MQTT server. Other MQTT clients, connected to an eNodeB, can subscribe to the MQTT server to receive the data they are interested in.

Publish/Subscribe Model

MQTT protocol is using a publish/subscribe model. The center piece of this mode is the use of what is called **topics**. MQTT devices are either a client or server. A client can publish messages to a topic. A Client can also subscribe to a topic that pertains to it and thereby receives any message published to this topic by any other client that publishes to this topic.

Topic and Subscription

Client in MQTT publishes messages to a topic (or a number of topics). A topic is typically a representation of subject areas. Client can sign up to receive particular messages by subscribing to a topic. Subscriptions can be explicit which limits the messages that are received to the specific topic at hand. Subscriptions can also use wildcard designators, such as a number sign (#), to receive messages for a number of related topics.

Appendix B

Amazon Web Services for IoT Devices (AWS IoT)

Amazon Web Services (AWS) is the Cloud offered by Amazon. Amazon Cloud is available worldwide and in different regions. AWS offers MQTT service where the MQTT server is hosted in AWS. NB-IoT devices, acting as MQTT client, can communicate with the AWS.

The AWS service for IoT is called AWS IoT and is available as a service offered by Amazon Cloud. AWS IoT allows you to easily connect NB-IoT devices to the Cloud. AWS IoT supports MQTT which is a lightweight communication protocol specifically designed to minimize the code footprint on devices, reduce network bandwidth requirements, and is commonly used for IoT devices. You will use MQTT to connect NB-IoT devices to the Cloud and make Arduino projects and sketches connect, upload, and download data to the Cloud.

AWS IoT connects to IoT devices by authenticating and providing end-to-end encryption to connected devices. Arduino sketches transmit and receive data to Cloud after performing authentication with the Cloud and data is encrypted in both directions.

With AWS IoT, you can filter, transform, and act upon device data on the fly, based on rules that can be defined on the Cloud. You can update your rules to implement new device and application features at any time. After a rule processes data received from devices, it can store these data for further visualization or processing such as storing it on the Cloud database such as Amazon DynamoDB.

The following figure shows the setup of the NB-IoT hardware board when connected to the Cloud. The cellular modem communicates with the cellular base-station (eNodeB) and connects to the APN in the mobile operator core network. The APN acts as a router that connects the modem to the Cloud.