ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

ELECTROMECHANICAL ENGINEERING

MODULAR ELECTRIC LONGBOARD

Author: Nicolás Triviño Carver
Director: Paul Scott Carney
(University of Illinois at Urbana-Champaign)

Madrid
June 2015

Proyecto realizado por el alumno/a:

NICOLÁS TRIVIÑO CARVER

Fdo.: …………………… Fecha: 07/ 05/ 2015

Autorizada la entrega del proyecto cuya información no es de carácter confidencial

EL DIRECTOR DEL PROYECTO

PAUL SCOTT CARNEY

Fdo.: …………………… Fecha: 07/ 05/ 2015

Vº Bº del Coordinador de Proyectos

FERNANDO DE CUADRA GARCÍA

Fdo.: …………………… Fecha: ……/ ……/ ……

MODULAR ELECTRIC LONGBOARD

Autor: Triviño Carver, Nicolás.

Director: Carney, Paul Scott.

Entidad Colaboradora: University of Illinois at Urbana-Champaign.

RESUMEN DEL PROYECTO

I. Introducción

Cada vez son más son más las empresas y las personas que apuestan por vehículos eléctricos, no solo porque son medios de transporte limpios que no contaminan, sino también porque representan el futuro. A día de hoy, son muchos los proyectos llevados a cabo en los que hemos visto como con la simple instalación de un motor se pueden conseguir productos muy interesantes y a la vez muy comercializables por su versatilidad, comodidad y precios relativamente reducidos. Una ventaja que suponen estos medios de transporte es que se pueden recargar en casa, en el trabajo o en cualquier lugar donde se disponga de un enchufe, haciendo de ello una novedad de la que muy pocos medios de transporte gozan.

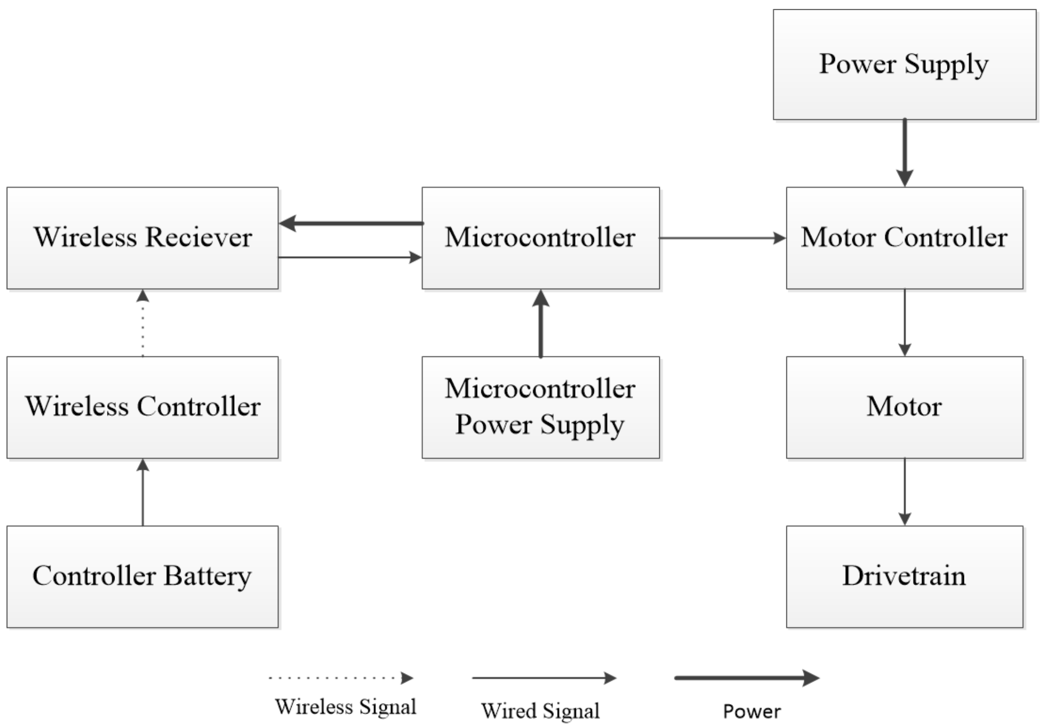
El objetivo de este proyecto es aunar todas las ventajas mencionadas en un solo producto, reducir el precio de venta de los monopatines eléctricos ya existentes en el mercado y añadir nuevas prestaciones que harán de este longboard uno mucho más accesible para todos aquellos que ya dispongan de una tabla, puesto que se podrá desmontar en un tiempo reducido.

II. Enfoque

La principal prioridad que este proyecto tiene es hacer que el producto fuera modular, es decir, que para todos aquellos usuarios que ya dispongan de una tabla, solo necesitarán compra el kit motorizado para encajar por debajo y transformarlo así en un monopatín eléctrico.

El diagrama de bloques que se muestra a continuación, presenta las diferentes piezas que se van a usar para completar este proyecto. Podremos distinguir de forma clara los dos tipos de comunicación que habrá: la comunicación inalámbrica (Wireless) y la comunicación por cable (wired). La parte inalámbrica será un mando a distancia que constará de tres botones para regular las tres diferentes velocidades, que serán programables por el usuario, un transmisor de señal (Xbee) y dos pilas AAA para encender el transmisor.

La parte cableada, constará de un microcontrolador, un recibidor de señal (Xbee), un motor brushless y dos baterías para accionar tanto el motor como el microcontrolador.



III. Proceso de Construcción

La construcción del longboard se dividió en tres fases, la primera fue la parte más matemática, donde gracias a los cálculos se pudo saber con mayor precisión qué características debían cumplir cada una de las partes que necesitaría para la elaboración del proyecto. Esta parte duró aproximadamente un mes ya que en el mercado no se comercializa lo que se estaba buscando. Por lo tanto tuvimos que adaptarnos a lo que estaba comercialmente y eso llevó en ocasiones a un proceso de prueba y error, que nos obligaba a recalcular para verificar si cumplía con cada uno de los requisitos.

Una vez seleccionados todos los elementos necesarios, comenzó la fase de montaje sobre la tabla del longboard. Lo primero fue diseñar muchas de las cajas, monturas y cajas de cambio que se iban a necesitar para que el resultado final cumpliese las expectativas que se fijaron desde el principio. A parte de realizar los modelos en CAD, había que elaborar el código que el microcontrolador necesitaría para hacer mover el motor. Después de una profunda investigación en internet, pude elaborar un código sencillo pero eficaz que se adecuaba a las prestaciones de velocidad que se fijaron, llegar a los 24 Km/h.

IV. Resultados

El resultado fue muy satisfactorio, todos los objetivos marcados se cumplieron. Además, el producto quedó con una estética muy lograda, y por ello surgió la idea de poner en marcha una campaña para su comercialización al público general. Será competitivo en el actual mercado ya que los precios de muchos de los productos relacionados son muy elevados en comparación con el precio al que se quiere vender este Longboard Eléctrico.

V. Conclusión

Este proyecto se podría resumir como la creación de un producto que representa la nueva manera de moverse por el mundo, un medio de transporte económico, sencillo y que cuida del medio ambiente. Hay mucho trabajo por delante, pero todo precisa de un comienzo para poder mejorarlo.

Como futuras prestaciones, se está recopilando mucha información de gente que le apasiona la idea y que quiere formar parte de este proyecto. Por adelantado puedo decir que se quiere trabajar en la idea de crear una *app* para sustituir el mando y como medio para regular la máxima velocidad a la que el usuario quiere llegar. También, se está trabajando en la idea de implementar un sistema de luces en la parte trasera del monopatín para que aquellos que quieran montarse por la noche puedan hacerlo con seguridad y puedan ser vistos por el resto de vehículos que circulan a su alrededor. Muchas son las ideas que este proyecto mueve a su alrededor y es por eso por lo que sería interesante que mi proyecto de fin de Máster tuviera relación con el Longboard Eléctrico.

EXECUTIVE SUMMARY OF THE PROJECT

I. Introduction

There are more and more companies and individuals who nowadays are betting on electric vehicles, not only because they are a green means of transport, but also because they represent our future. At present, there are many different interesting projects that have become successful thanks to the installation of a simple motor, making them very marketable due to characteristics such as versatility, convenience and reduced prices. An advantage that these means of transport posses is that the battery can be recharged at home, at work or anywhere where there is access to a plug, making this feature a big change for any vehicle that currently exists on the market.

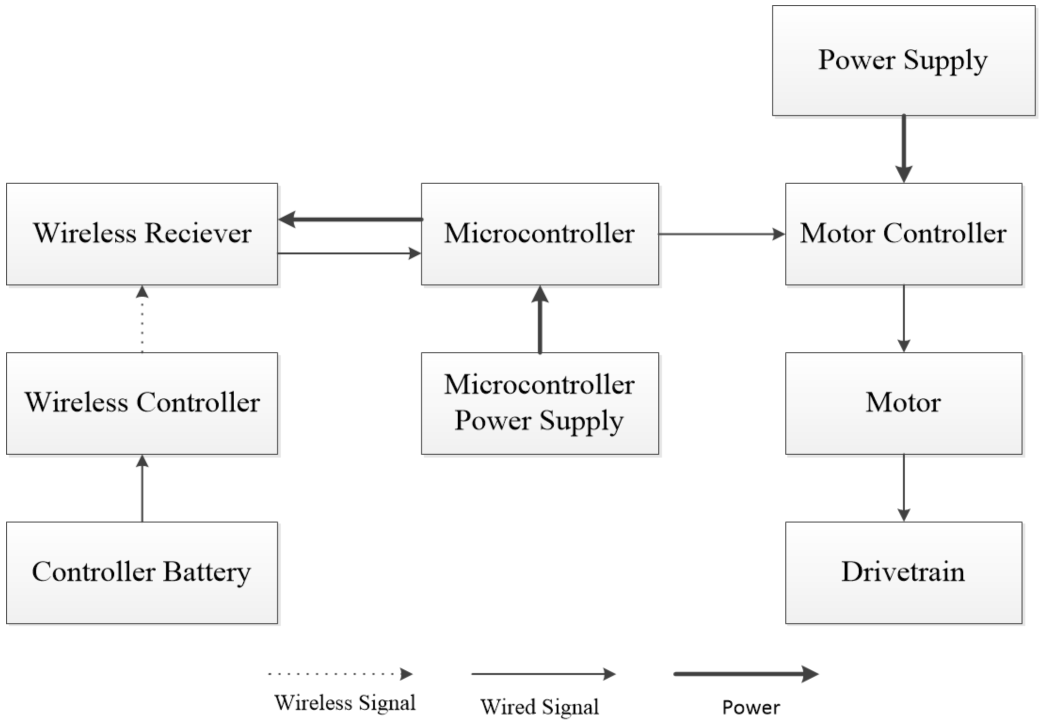
The aim of this project is to reunite all of the advantages mentioned above in one single project, reduce the price of the now existing electric longboards on the market and add new features which will allow all users who already have a longboard to install the motorized kit that this project offers.

II. Approach

The main objective of this project is to make the longboard modular, which means that those users who already have a longboard will only need to buy the motorized kit and install it underneath their board to transform it into an electric longboard.

The block diagram that is shown, presents the different parts that this project involves. We can appreciate two types of communication; wireless and wired. The wireless side consists of a remote control with three buttons to allow the user to achieve the speed desired. This remote control will be built with a signal transceiver (XBee) and two AAA batteries to run the Xbee.

The wired part will consist of a microcontroller, a receptor transceiver (XBee), a brushless DC motor, two batteries to run the motor and the microcontroller and an electronic speed controller.



III. Building Process

The building process was divided into three parts. The first part was dedicated to the mathematical perspective of the project, where, thanks to all of the calculations carried out it made it possible to know with higher precision what characteristics each of the parts had to meet. This part lasted for at least a month due to the fact that parts with the exact calculated specifications could not be purchased therefore I had to adapt what was available on the market and consequently at various points it was a trial and error process, which made me recalculate and verify that all the requirements were still met.

Once all of the parts were chosen, the building process began. The first thing to do was to design the boxes, mounters and gear ratios that were going to be needed to ensure that the final results were the same as those determined at the beginning of this project. Once the CAD was done, I needed to design the code for the microcontroller to enable the motor to move. After research, I was able to create an easy but effective code making the performance of the electric longboard achieve what was expected - a speed of 24 Km/h.

IV. Results

The results were very satisfactory and all the objectives were met. Also, the product was esthetically pleasing and it was at that point when the idea of creating a campaign to commercialise this project arose. It is a product that is competitive on the current market since almost all of the other electric longboards have very high prices making the product inaccessible for many users who are passionate about the idea.

V. Conclusion

This project can be summarised as the creation of a product that represents a new way of traveling, an economic means of transport, easy and green. There is still a great deal of work to be done, but as always there has to be a starting point for something to be improved.

With a view to carrying out a new project in the future, I am compiling information of people who are passionate about the idea and who would love to be part of this project. In advance, I will say that an *app* for any smartphone is being developed in order to substitute the remote control and also to programme the speeds that the user wants to achieve. I am also working on the idea of implementing a night light system to allow users to ride safely when it is dark making them visible for other vehicles.

The electric longboard promotes many interesting ideas and for this reason I would love to continue working on further development of the project when I finish my Master’s as part of the Master’s Project I will have to complete.

Table of Contents

Table Index

Figure Index

Part I.

Memory

1 Introduction

On a college campus, there are various modes of transportation that students can use to get to class every day. Some walk, some ride a bike, most ride a bus, but there is a growing number of students who choose to ride a longboard to class. Despite the convenience of longboarding, there is one key problem with riding a longboard to class: it is extremely tiring. The goal is to create an attachment that will be used to convert any longboard into an electric powered longboard.

I know that there are other electric longboards on the market, but they have one drawback which is the fact that everything is screwed to the board, thus not allowing the freedom of removing the whole kit if you ever feel like just longboarding with a lighter board. A few other problems that these electric longboards face are related to speed, weight, autonomy of the battery, controls, and price. Knowing all of this we are determined to try and create a better electric longboard, focusing on the concept of making it adjustable and removable for any board on the market.

1.1 State of the art

There are already some products on the market as we can see in table 1, but many of their features; price, weight, speed, for example, are sufficient reasons to make a customer think about buying it or not.

Company	Weight (lbs.)	Price ($)	Range (Miles)	Max. Speed (Mph)	Aesthetics	Controls
ZBoard	25-33	650-1200	5-18	15-18	Bulky, Ugly	Pressure Sensor
Boosted	13-15	1000-1500	6-7	18-22	Streamlined, modern	Handheld Wireless
E-Glide	35-72	700-1200	6-15	18-23	Bulky, Small	Handheld Wireless
Evolve	18-23	1300-1600	9-27	22-24	Streamlined (mostly)	Handheld wired
Marbel	9.5	1300-1500	10-15	25-28	Minimalist	Handheld Wireless

Table 1.1. Market analysis

1.2 Objectives

1.2.1 Goals

- Be in "*Table 1*" without any of our features in red
- Make our product as esthetically pleasing as possible
- Keep our product at a weight that would make sure that the complete longboard would not weigh more than 20lbs.
- Make it safe during night time

1.2.2 Benefits

- Environmentally friendly
- Fast means of transport
- Easy to release from the board
- No physical effort to achieve high speeds
- The product can be easily attached to any existing deck
- Easy to carry

1.2.3 Features

- Longboard will be able to speed up to 15 mph
- Small handheld controller that fits inside your hand
- Safe attachment so no wires are displayed
- Kill switch

2 DC motors

Nowadays, DC motors have many characteristics that make them very attractive, such as high efficiency, simple control that does not require complex hardware, linear torque-speed characteristics. However, some of its drawbacks are that the brushes need periodic maintenance or need to be replaced and that they make noise. On the other hand, Brushless DC Motors (BLDC), solve these main problems. These motors, despite the name, are very similar to permanent magnet synchronous motors. They work with DC voltage but current is obtained from a commuting system. Depending on the position of the rotor, which is calculated with either sensors or sensorless techniques, current is applied to the motor, as we will see later.

Feature	BLDC Motors	Brushed DC Motors
Commutation	Electronic commutation based on Hall position sensors.	Brushed commutation.
Maintenance	Less required due to absence of brushes.	Periodic maintenance is required.
Life	Longer.	Shorter.
Speed/Torque characteristics	Flat – Enables operation at all speed with rated load.	Moderately flat – At higher speeds, brush friction increases, thus reducing useful torque.
Efficiency	High – No voltage drop across brushes.	Moderate
Output Power/ Frame Size	High – Reduced size due to superior thermal characteristics. Because BLDC has the wining on the stator, which is connected to the case, the heat dissipation is better.	Moderate/Low – The heat produced by the armature is dissipated in the air gap, thus increasing the temperature in the air gap and limiting specs on the output power/frame size.
Rotor Inertia	Low, because it has permanent magnets on the rotor.	Higher rotor inertia.
Speed Range	Higher – No mechanical limitation imposed by brushes / commutator.	Lower – Mechanical limitations by the brushes.
Electric Noise	Low.	Arcs in the brushes will generate noise, causing EMI in the equipment nearby.
Cost of Building	Higher – Since it has permanent magnets, building costs are higher.	Low.
Control	Complex and expensive.	Simple and inexpensive.
Control Requirements	A controller is always required to keep the motor running. The same controller can be used for variable speed control.	No controller is required for fixed speed; a controller is only required only if variable speed is desired.

Table 2.1 BLDC v DC motors

2.1 BLDC Motors

2.1.1 Construction

A BLDC Motor as mentioned before is like a permanent magnet synchronous motor that uses sensors to detect the position of the rotor and inverters to control the current. These types of motors are commonly known as an inside-out DC motor since the armature is part of the stator and all the magnets are built on the rotor. Rather than using mechanical commutator, they use electronic commutation, which allows this motor to almost have zero maintenance.

BLDC Motors depend on how the winding is connected in the stator; trapezoidal and sinusoidal. In the trapezoidal motors, the back-emf have a trapezoidal shape and all phases must be fed with almost square waves, thus, the torque will suffer ripple during operation. Sinusoidal motors, on the other hand, have sinusoidal back-emf and also require sinusoidal currents for non-ripple torque operation. A big difference between both of them is that sinusoidal motors require knowing the position of the rotor at all times and thus high resolutions sensors need to be implemented making software very tedious.

The rotor is built with permanent magnets and its pair of poles can vary depending on the application required. Depending on the magnetic field needed in the rotor, magnets can be made from many different materials but they are commonly made of ferrite.

For better understanding, figure 1 represents a schematic where a motor with two poles and three phases is shown; windings of the stator (a, b, c), which are exactly the same but separated from each other by120º (2π/3 radians), each one of them with N_s spins and has a resistance R_e. Each winding from the stator generates a magnetic field distributed either trapezoidal or sinusoidal, which are represented in the figure as (shaft a, b and c) and the magnetics shafts of the rotor are represented as (shaft d and q). θ_e represents the angle between the shaft *a* and *d* and ω_e the speed at which magnetic field spins.

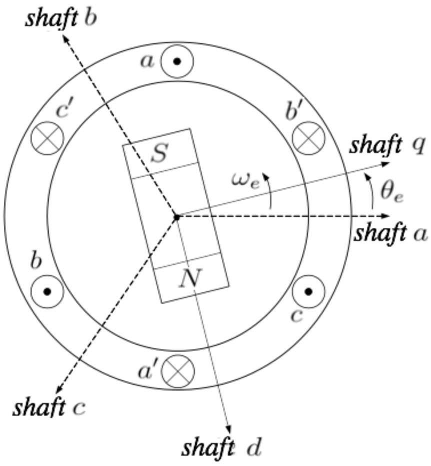


Figure 1. Transversal section of the stator

2.1.2 Operation

A big difference between brushed and BLDC as stated in Table 2 is that these last ones are always controlled electronically with an ESC or motor controller. It is very important to know the position of the rotor in order to understand how each sequence works, and for this reason Hall sensors must be integrated in the stator. There are typically three of them and they are in charge of sending a signal (High or Low) whenever a North pole or a South pole is near to them. Hall sensors are commonly supplied with 4 to 24V and a current that can vary from 5 to 15mA.

Figure 2 represents a simplified illustration of a BLDC motor construction. Electrical energy is converted into mechanical energy by the magnetic attractive forces between the permanent magnet rotor and the rotating magnetic field induced in the wound stator poles. Most of the BLDC motors have a three-phase winding topology with star connection. Each of the commutation sequences belongs to an activation state of the coils, meaning that one of the windings has a positive voltage (current goes inside the winding), a second winding has a negative voltage (current goes out of the winding) and a third one is not activated.

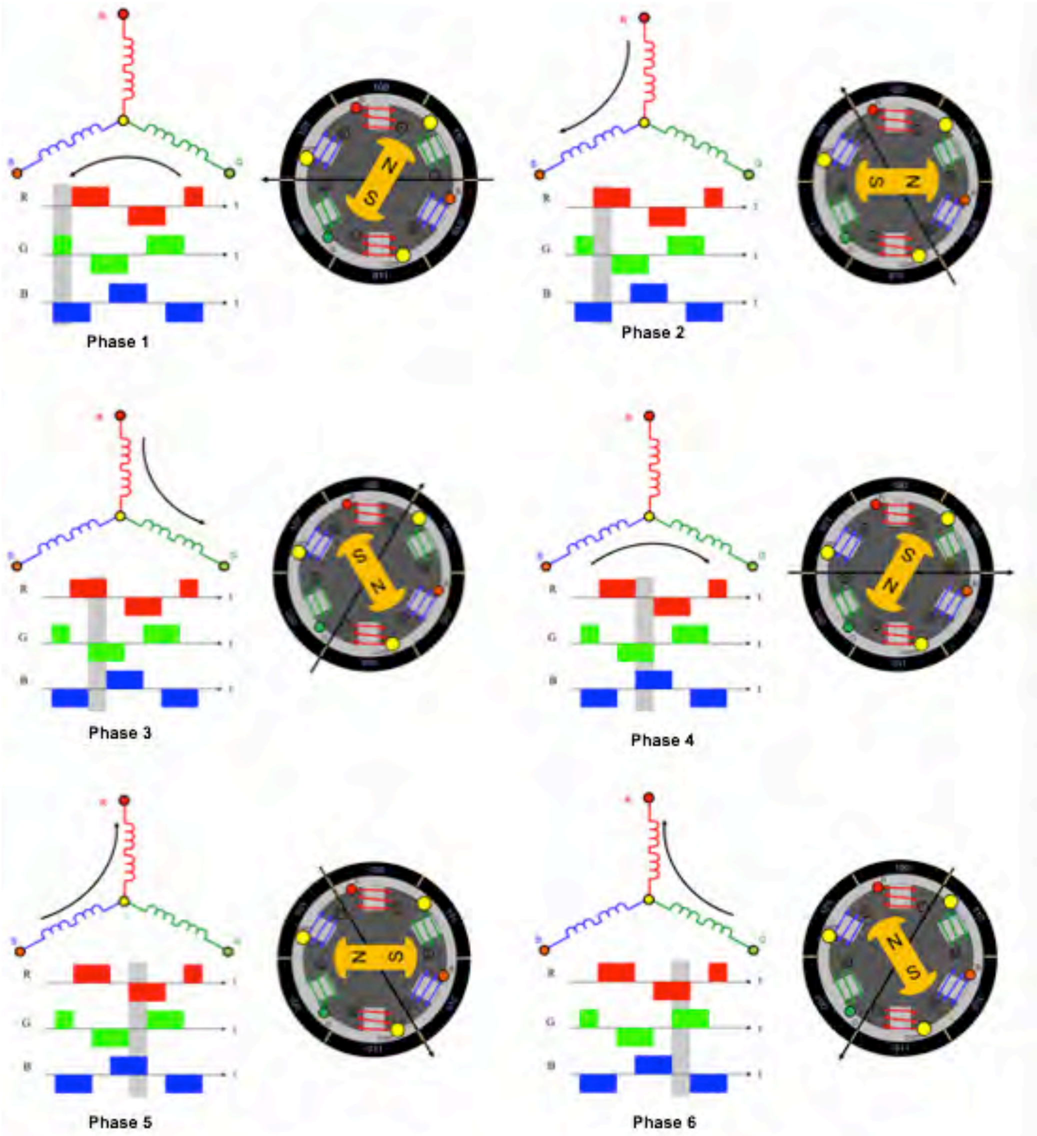


Figure 2. Commutation sequence of coils

The schematic illustrated in figure 2 shows this commutation representing current flow and back-emf all 360 electrical degrees. As we can see, sensing the rotor position is very important, the reason behind this is that energizing the correct phase will produce the highest amount of torque. The rotor travels 60 electrical degrees per commutation step. The appropiate stator current path is activated when the rotor is 120 degrees from aligment with the corresponding stator magnetic field, and then desactivated when the rotor is 60 degrees from aligment, at which time the next circuit is activated and the process repeats.

2.1.3 Mathematical Model

In this section, I will demonstrate what is the equivalent circuit attached to the BLDC motor. Following, I will calculate the flux in the rotor and in the stator. Then, I will do a power analysis for a better understanding of what outputs to expect of the BLDC Motor and finally I will show the torque/speed characteristic.

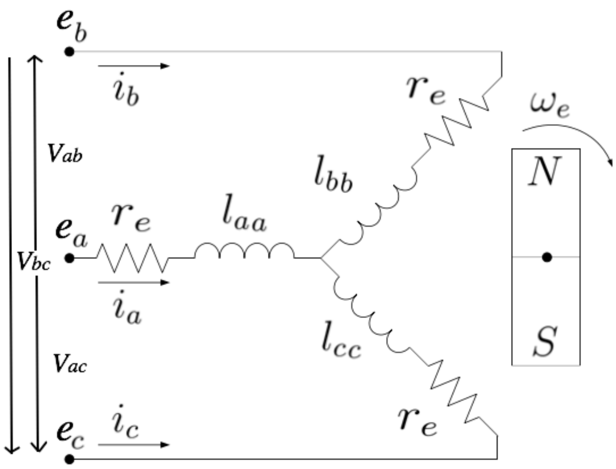


Figure 3. Windings of the stator

As mentioned before, star connection is the most common connection and each winding is represented by a resistance, (R_e, which will be the same in every winding due to construction) and a coil (l_{aa}, l_{bb} and l_{cc}) figure 3, represents a schematic of it and all the variables associated. i_a, i_b and i_c are the currents that flow through each winding; e_a, e_b and e_c are the back-emf's respectively, in the three phases a, b and c; V_{ab}, V_{bc} and V_{ac} are the phase-to-phase voltages; T_e is the torque the motor is supplying; T_l the load torque; J is the rotor inertia and B_0, B_1, B_2,..., B_n are friction constants.
The three-phase star connected BLDC motor can be described by the following four equations:

$$V_{ab} = R_e(i_a - i_b) + L\frac{d}{dt}(i_a - i_b) + e_a - e_b \quad (2.1)$$

$$V_{ac} = R_e(i_a - i_c) + L\frac{d}{dt}(i_a - i_c) + e_a - e_c \quad (2.2)$$

$$V_{bc} = R_e(i_b - i_c) + L\frac{d}{dt}(i_b - i_c) + e_b - e_c \quad (2.3)$$

$$T_e - T_l = J\frac{d\omega}{dt}(B_0 + B_1\omega + B_2\omega^2 + \cdots) \quad (2.4)$$

Where e_a, e_b e_c,, i_a, i_b and i_c can be defined by the following equations:

$$e_a = V_m \cos(\omega_e t)$$
$$e_b = V_m \cos(\omega_e t - \frac{2\pi}{3}) \tag{2.5}$$
$$e_c = V_m \cos(\omega_e t + \frac{2\pi}{3})$$

$$i_a = I_m \cos(\omega_e t - \varphi)$$
$$i_b = I_m \cos(\omega_e t - \varphi - \frac{2\pi}{3}) \tag{2.6}$$
$$i_c = I_m \cos(\omega_e t - \varphi + \frac{2\pi}{3})$$

I_m, V_m are the maximum amplitudes of the current and voltage respectively and φ is the angle whose angles is the power factor at which our motor operates. Note something important from these equations, and it is that when all three-phase have the same amplitude, the following equations have to be satisfied.

$$e_a + e_b + e_c = 0 \tag{2.7}$$
$$i_a + i_b + i_c = 0 \tag{2.8}$$

Knowing what each of the variables mean and how they can be calculated, flux can be easily determined as it is shown in equation 2.9.

$$\lambda_a = l_{aa} i_a + l_{ab} i_a + l_{ac} i_a + \lambda_{am}$$
$$\lambda_b = l_{ba} i_b + l_{bb} i_b + l_{bc} i_b + \lambda_{bm} \tag{2.9}$$
$$\lambda_c = l_{ca} i_c + l_{cb} i_c + l_{cc} i_c + \lambda_{cm}$$

Where $\lambda_{am}, \lambda_{bm}$ *and* λ_{cm} is the flux produced by the magnet and its value depends on the material in which the magnet is done.

Our BLDC motor transforms electric power into mechanical power that is applied to the rotor but in this process there are some losses:

1. Electric power input: It is the power supplied in the windings of the stator and it can be calculated as equation (2.10) shows. This power does not depend on the type of connexion (Δ or γ).

$$P_{in} = 3V_{\phi}I_{\phi}cos\varphi = \sqrt{3}V_L I_L cos\varphi \tag{2.10}$$

2. Losses in the resistance: These losses are transformed into heat and to calculate them we use Joules law.

$$P_R = 3|I_a|^2 R_a \tag{2.11}$$

3. Mechanical Losses: The friction of the moving parts inside the motor and the friction with the air produce these losses.

4. Iron losses: These losses occur when the motor starts heating up and do not really have to be taken into account when speed is under 5.000 rpm. Eddy currents also appear due to changing magnetic flux, but they are not relevant unless we surpass the 20.000 rpm.

5. Mechanical Power: This is the result of subtracting from the input power all the losses.

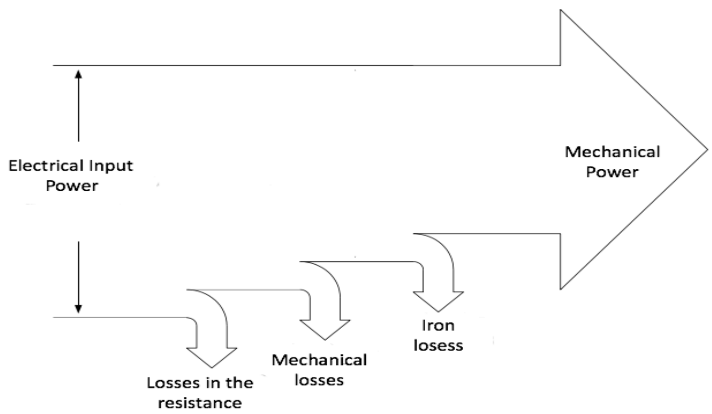


Figure 4. Power diagram

Figure 5 shows an example of what a Speed/Torque characteristic of a BLDC Motor can look like. There are three parameters that are important in this graph and are the Peak torque (T_P), the Rated torque (T_R) and the Rated speed. By knowing these three variables and how they are related, we can build an approximation for our specific motor.

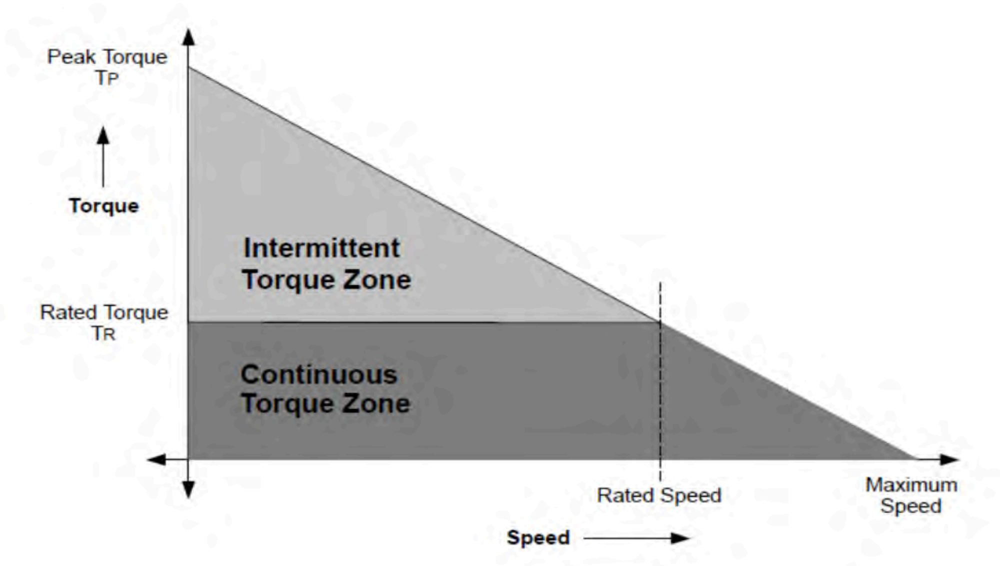


Figure 5. Speed/Torque Characteristic

As we can see in the figure, the relation between the speed and the torque is linear, making mathematical operations very easy to calculate. Two of the important equations that we must take into consideration are:

$$Max.RPM = KV * DC\ Battery\ (V) \tag{2.12}$$

$$M = KT * I(A) \tag{2.13}$$

These two equations allow us to calculate the maximum speed and torque as a function of the current and the DC battery. KV and KT are constants that are fixed and depend on each BLDC motor. KT constant represents the torque the motor can give per amp flowing and the KV constant represents the speed at which the motor can spin per volt applied.

As we can see, the higher the battery we use, the higher speed we obtain, but if we look back to figure 6, we see that the faster our motor spins, the less torque we can give and that may be a problem depending on our goal, and for this reason, gear ratios are commonly used.

You might be wondering if there is any relation between both constants, KV and KT, and as you can imagine there is. This equation is very simple but we have to be careful with one thing, units.

It is very common that KV constant is given in RPM/V, but in equation 2.14 we have to convert it to rad/(sV).

$$KT = \frac{1}{KV}\left(\frac{sV}{rad}\right) \tag{2.14}$$

Note that $\left(\frac{sV}{rad}\right)$ is the same as $\left(\frac{Nm}{A}\right)$ but we will leave this to the reader.

Since most of the suppliers just provide the KV constant, depending on the application, we will be looking for a higher or lower rate. If what we need is high torque, we will need a low KV rate but this will translate into lower speeds. If however what we want is high speed but we do not really need high torque, what we will be looking for is a high KV constant.

2.2 Motor Controller (ESC)

The Motor Controller or Electronic Speed Controller is an electrical circuit in charge of controlling how much power the motor needs to run at a certain speed. The ESC is connected to the DC battery and it converts the signal into a three-phase input for the motor. To do this conversion from DC to AC, ESC's have integrated on its circuit transistors, typically FET's, and are moved via Pulse Width Modulation (PWM).
Figure 7 shows a schematic of how the DC battery, the ESC and the motor is connected.

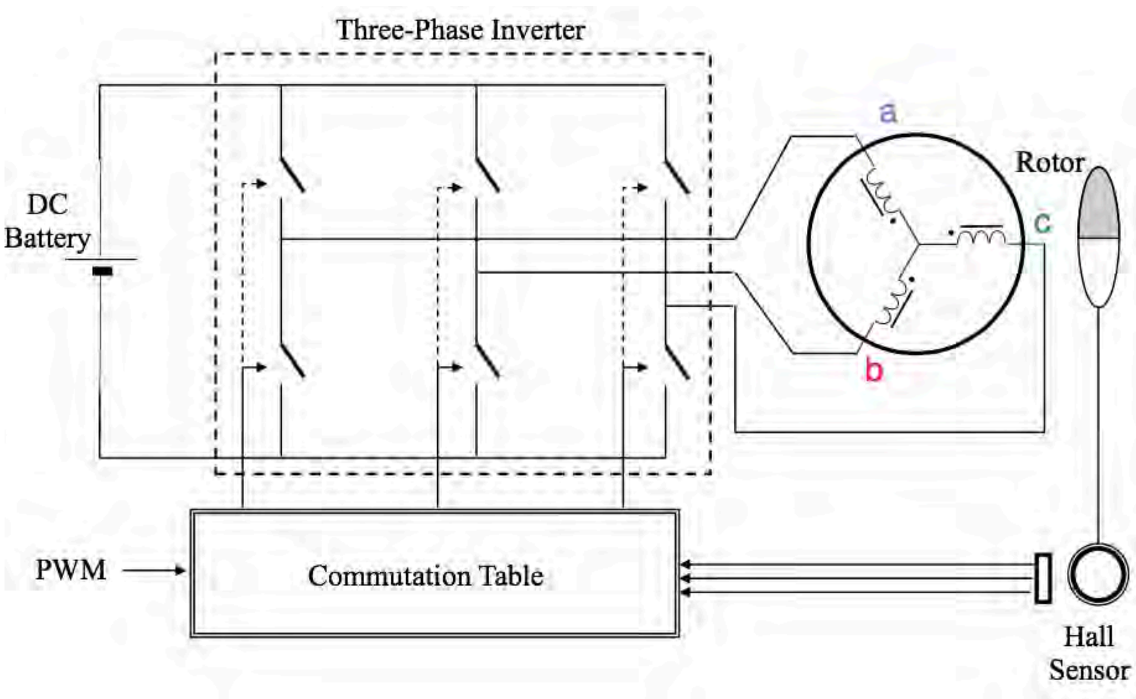


Figure 6. Schematic of connection

For a better understanding, I will show what the possible circuits we can obtain from the three-phase inverter are. Following, Table 3 will analyse what each of the six states of the inverter mean, describing which mosfets are on, which ones are off, voltage going to the motor and at the end figure 8 will interpret what Table 3 is trying to explain.

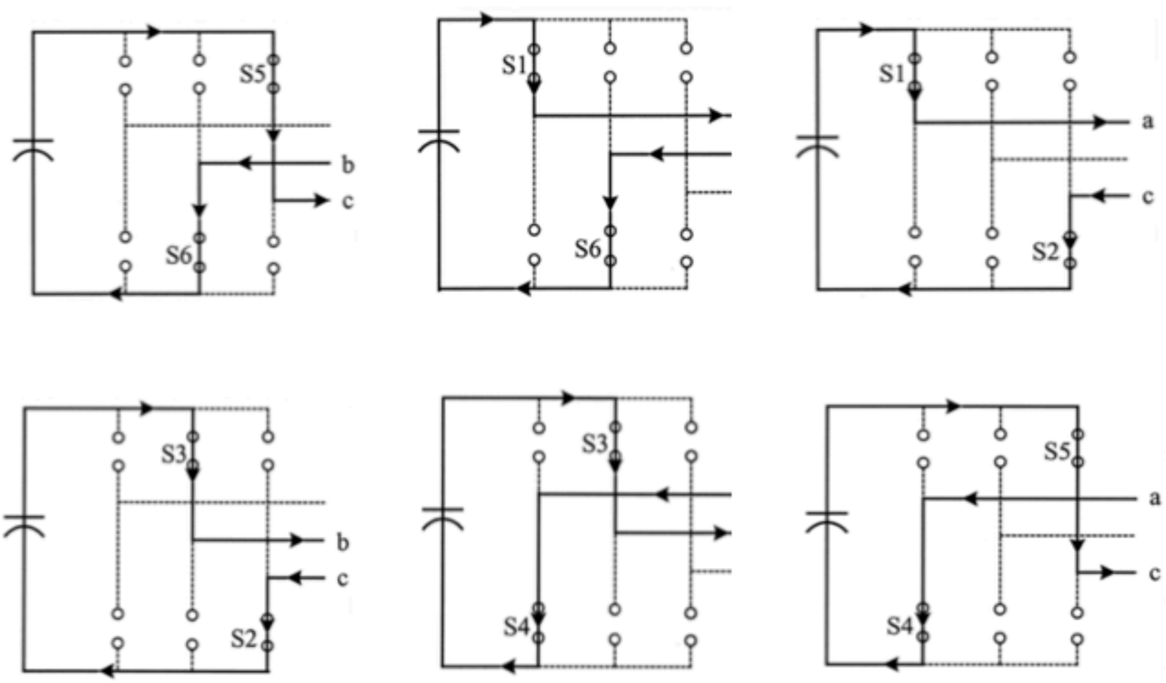


Figure 7. Configurations of the three-phase inverter

Switching Interval	Seq. Number	Pos. sensors			Switch Closed		Phase Current		
		H1	H2	H3			a	b	c
0° - 60°	0	1	0	0	S1	S4	+	-	off
60° - 120°	1	1	1	0	S1	S6	+	off	-
120° - 180°	2	0	1	0	S3	S6	off	+	-
180° - 240°	3	0	1	1	S3	S2	-	+	off
240° - 300°	4	0	0	1	S5	S2	-	off	+
300° - 360°	5	1	0	1	S5	S4	off	-	+

Table 2.2 Switching sequence

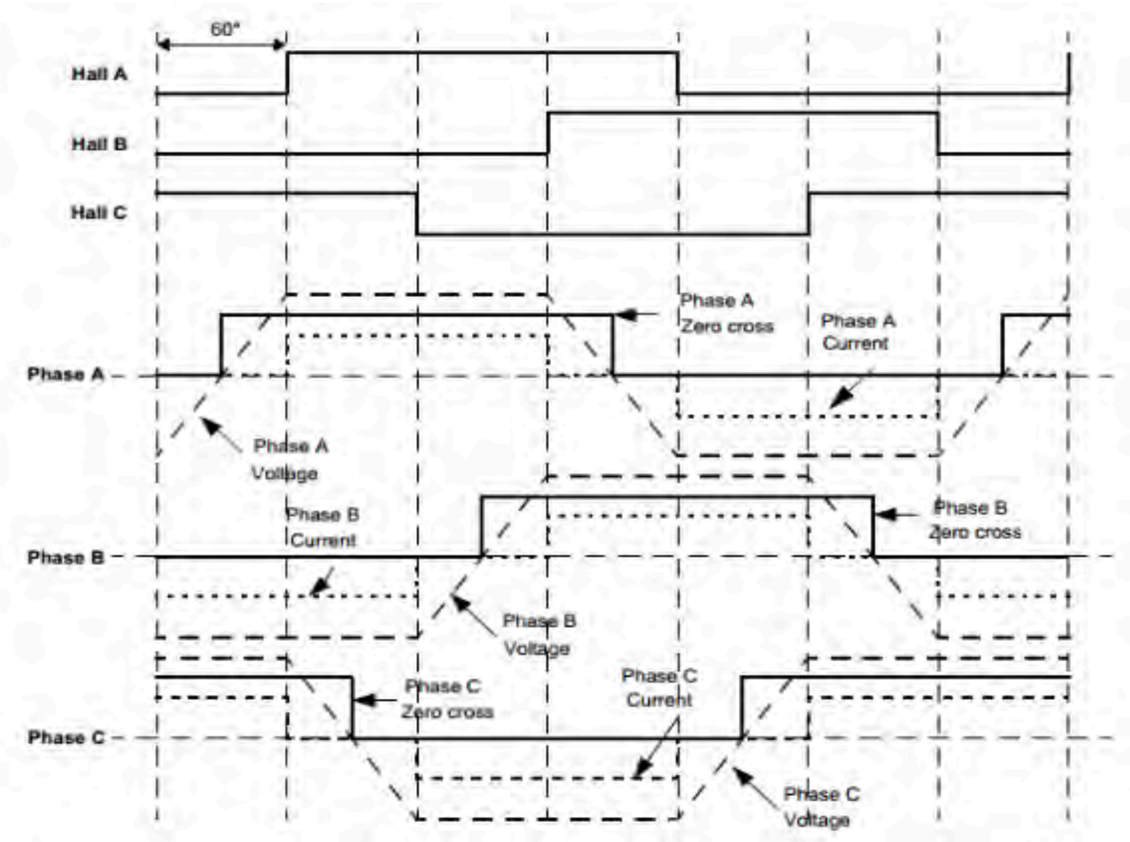


Figure 8. Hall sensor, Back-emf and current

3 Design

3.1 Block Diagram

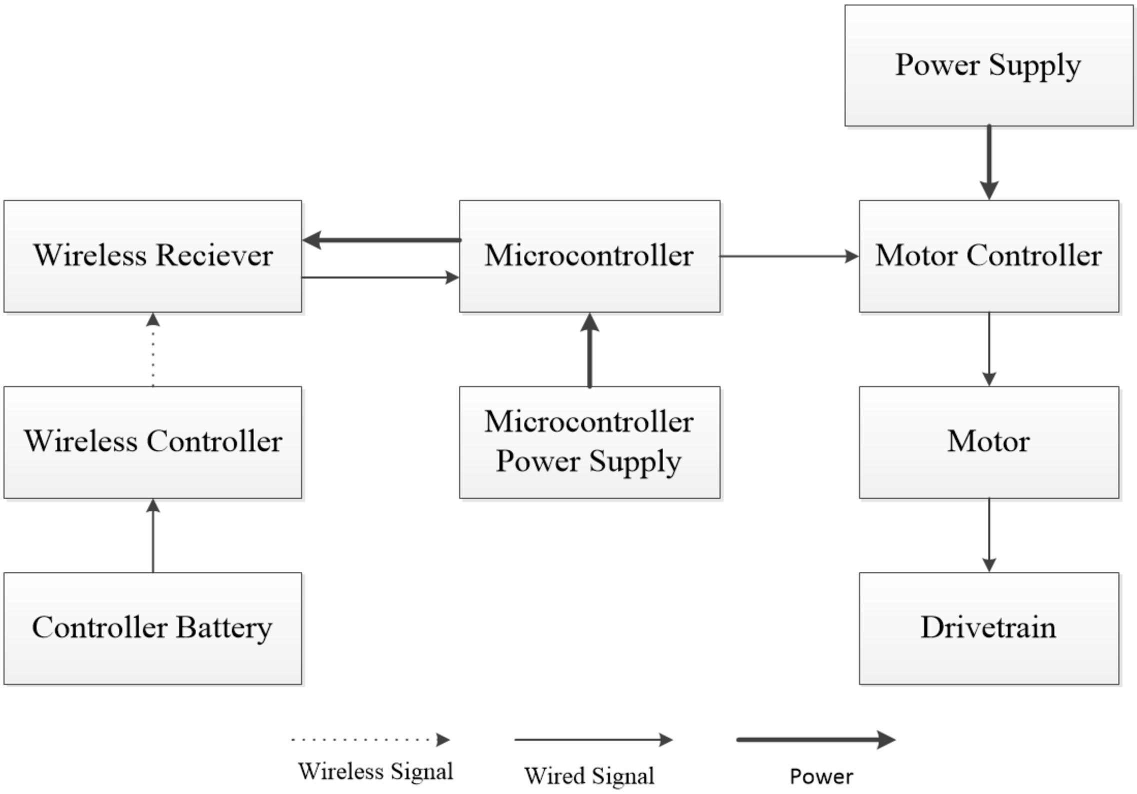


Figure 9. Block diagram of parts

This block diagram shows the connection between all of the parts that we have used for this project and how do they interconnect with each other.

In the next point, I will give a brief summary of the meaning of each of the parts and will provide some of the calculations that had to be done for some of the modules that were bought to build the project.

3.2 Modules

3.2.1 Wireless Controller

The wireless controller is the interface with which the rider communicates with the electric longboard. It is made up of an XBee, three push buttons, and a battery pack which takes two AAA batteries. All of these components are housed inside of a custom made, 3D printed case designed in sketch-up. The wireless remote works by connecting the three push buttons to the XBee and when one of the buttons is pressed a digital low signal is sent to the corresponding pin of the XBee on the microcontroller. The pin layout of the XBee and buttons on the controller can be seen in the appendix.

3.2.2 Transceiver

The XBee was chosen as a means of communication because it was an affordable option and was compatible with our microcontroller and has low power consumption. In this way the batteries in the controller can have a long lifespan that removes the worry of having to replace them often, so as to keep the controller functioning. The specific XBee used was a Series 1, which communicates through radio frequencies. The method of communication used was digital I/O line passing which communicates the signal on the input pins of the transmitter to the corresponding pins of the receiver. For our purposes, the signals on the pins were always set to digital hi, until one of the buttons was pressed changing the signal to digital low. This signal was then sent to the transmitter, which was connected to the microcontroller.

3.2.3 Microcontroller

The microcontroller that we chose is the Intel Galileo Gen 2. The microcontroller is responsible for receiving the signal from the wireless transceiver, which takes input from the wireless controller and converts that input into usable information for the electronic speed controller (ESC). The output to the ESC is a PWM (Pulse Width Modulation) signal, which is a pulse of 5V with varying width depending on the selected speed. The code for the esc is the same as if controlling a servo. Using esc.write(X), where X is a value above 60, outputs a certain PWM signal depending on the value of X. The code for the Galileo is included in Appendix B. A pin layout of the Galileo and associated XBee can be seen in the appendix.

3.2.4 Microcontroller Power Supply

The Galileo microcontroller had its own power supply separate from the motor power supply. This was done to increase the battery life of the board and in turn increasing the range. The Galileo can accept any voltage from 7-12V, so we went with a 3S 11.1V 3200mAh LiPo battery. The 3200mAh gives us enough capacity to outlast the motor power supply yet be small enough to not take up much space in our box.

3.2.5 Motor & Drivetrain

The motor chosen was the NTM Prop Drive 50-60 270KV / 2400W model, which is a brushless dc motor. It was the core component of the project, and was chosen through research and calculations. We chose a brushless dc motor because we found that they can provide a high torque at low voltage and they can be very small. The torque consideration comes in with the KV constant that is the rating that provides the voltage necessary in order to spin the motor at a certain RPM. This would play a key part in choosing the power supply for our motor.

The calculations performed were for the RPM of the wheel required to accelerate the user up to 15mph, the gear ratio to use, and the RPM of the motor based off of the gear ratio. The first step in this series of calculations was to find the speed of the wheel required in order to accelerate the user to 15mph, knowing that the diameter of the wheel is 83mm, which can be seen in the calculation below:

$$RPM_{wheel} = \frac{v}{c(60)} = \frac{21140.2\ {}^{m}/_{hr}}{0.083\pi * 60} = 1543\ rpm$$

Through research we found that this RPM was too low for a brushless dc motor to operate at continuously. This is due to the fact that the lower RPM of the motor, the lower the efficiency of the motor, which correlates to high current and power consumption. This can be seen in figure 10.

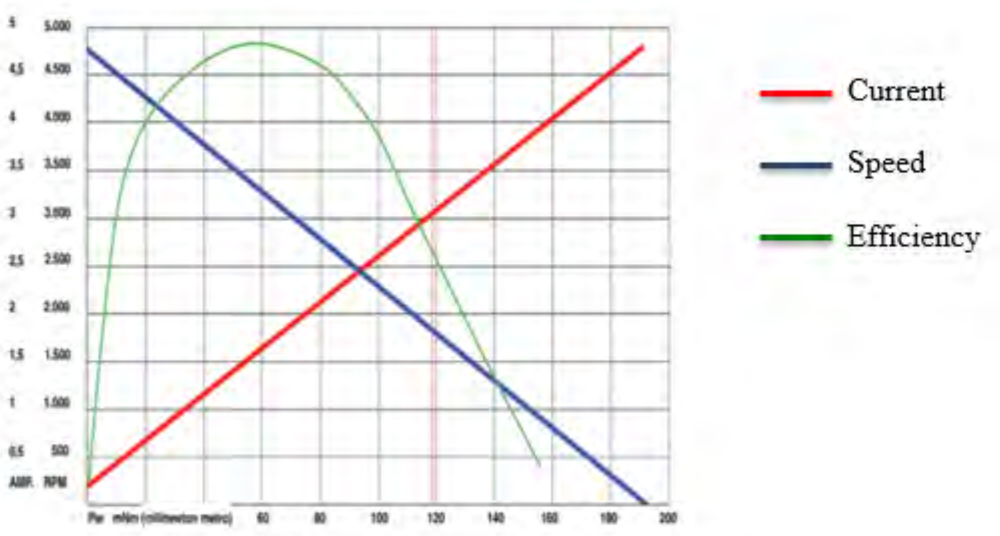


Figure 10. Current, Speed and Efficiency

Due to this, we decided to use a gear ratio in order to increase the RPM of the motor to an acceptable value. We chose a 3:1 gear ratio because that gave a value for the motor RPM to be:

$$RPM_{wheel} = Gear\ Ratio * \ RPM_{wheel} = 3 * 1543 = \ 4629\ rpm$$

This value of RPM is much better for the longevity of the motor and continuous operation. A larger gear ratio could have been used but due to size constraints of the gears, we decided to stick with a 3:1 ratio.

3.2.6 Motor Controller

The motor controller, also known as the electronic speed controller is the interface between the microcontroller and the motor. It takes PWM signals from the microcontroller and converts the dc voltage of the motor power supply into three-phase ac voltage based on the width of the signal. It then applies that voltage to the motor, making the motor spin. The specific ESC used was chosen because it was designed to work with a brushless dc motor, a LiPo battery, and because it met the top current rating of the motor.

3.2.7 Motor Power Supply

The motor power supply was calculated using the KV constant of the motor, which was 270 RPM/V for the motor we have bought. This calculation can be seen below:

$$V_{battery} = \frac{RPM_{motor}}{KV\ Constant} = \frac{4629\ rpm}{270\ rpm/V} = 17.14\ V$$

The battery voltage above rounds to an 18V battery. The voltage of batteries is based on the number of cells contained within the battery, each cell providing 3.7V. This voltage then leads to a five-cell battery by dividing the voltage required by the voltage per cell. However we decided to go with a six cell, 10,000mAh battery due to availability on the market and capacity desired in order to reach the range of operation originally stated.

4 Design Verification

4.1 Controller

4.1.1 Battery

The XBee takes at least 2.5V to power it. Instead of getting another rechargeable battery we went with two AAA batteries. Each AAA battery is rated at 1.5V, so putting them in series should result in 3.0V being output. When connected to a multimeter the observed voltage was 2.84V.

4.1.2 Transceiver

The XBee's used digital I/O line passing. When the input on the transmitting XBee changes the corresponding pin on the receiving XBee also changes. Three of the input pins on the transmitting XBee were each connected to a pushbutton, which was then grounded on the other side. This means the pins on the receiving XBee are set to high, or 3.3V, and will go low when a pin on the transmitting XBee is grounded by pressing a button. To test the communication the receiving XBee had LEDs on the three pins and the transmitting XBee had the pushbuttons. When no buttons are pressed the LEDs are all on, but when one button on the transmitting XBee is pressed the LED connected to the same pin on the other XBee turned off.

4.2 Longboard

4.2.1 Microcontroller

The output to the electronic speed controller is different for the three speeds. We connected the Galileo to an oscilloscope and measured the output for each of our speed settings. As we went from low to medium to high we observed the width of the pulses increase. The widths were 1.305ms, which corresponds to low speed, 1.46ms that corresponds to medium speed, and 1.715ms, which corresponds to high speed as observed in figure 11.

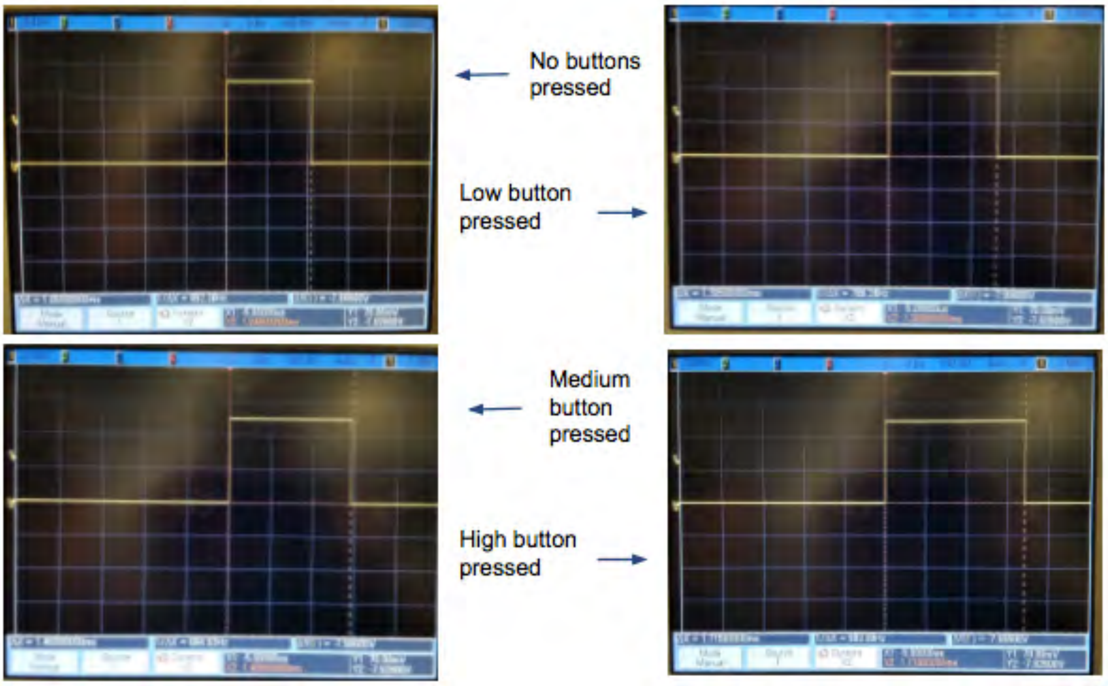


Figure 11. PWM for no buttons pressed, low, medium and high speed

4.2.2 Motor

The motor was tested with the entire board put together. The test was done on the high-speed setting since that is when we achieve 15 mph. The speed was obtained using GPS on a phone.

4.2.3 ESC

The electronic speed controller needs to be armed first before it can accept inputs. All esc's make a series of beeps for things like startup mode, brake, battery type and timing. The one that we care about is the startup mode. Our esc will make six short beeps followed by two long beeps to indicate it is armed and ready to go. We loaded up just the arming code in the Galileo to check the esc arms. We did this several times and each time the esc made the series of beeps indicating arming.

4.2.4 Batteries

The two batteries were tested by hooking them up to a multimeter. The battery powering the motor should be 22.2V ± 10% and the micro-controller battery should be 11.1V ± 10%. They were measured to be 24.04V and 12.2V respectively. This meets the requirements stated on the Requirements and verification table.

5 Ethical Considerations

1. ‘’ To accept responsibility in making decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment” [7]

   In order to mitigate risk involved with motorizing a longboard, a helmet and pads should be worn at all times and the rider should evaluate their skillset with that required of riding a motorized longboard. The board was tested away from traffic and busy streets in the interest of public safety and was operated by an experienced rider to mitigate any risk involved.

3. “To be honest and realistic in stating claims or estimates based on available data” [7]

   All claims of speed, battery life, acceleration, and modularity were calculated and tested thoroughly in order to achieve these standards. In this way the data provided by us is as honest and realistic as possible.

7. “To seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others” [7]

   Throughout the senior design process we will accept and use criticism received in a constructive manner in order to advance our end goal of creating a modular electric longboard.

9. “To avoid injuring others, their property, reputation, or employment by false or malicious action” [7]

   Only high quality parts were used, and the parts used can be seen in the parts cost list in order to advance the safety of the consumer and the honesty of our endeavour.

6 Conclusion

Throughout the course of the semester, I was able to achieve the design and creation of a modular electric longboard. This longboard design met all of our goals set at the beginning of the semester, which were to create an electric longboard that could be easily disassembled in less than 10 minutes, could accelerate a rider to 15 mph, and could safely traverse at least six miles on one charge.

Due to time and problems faced during the semester, there were some features that were not included, but the department of Electrical and Computer Engineering of the subject ECE 445 still awarded the project as the best mean of transport out of all of the groups that were part of this subject. This award, not only motivates me to continue with the project but also to keep on working hard on my modular electric longboard trying to fix minor problems that I faced and also to try and reduce the cost of parts in order to consider a possible commercialization of the product since it is a product that can compete among the rest of the companies that are selling a similar product.

7 Future Work

There is one uncertainty at this point and that is the motor mount. Currently the way that the motor is mounted onto the board leaves very little clearance between the riding surface and the mount. This means that the rider must be careful to avoid large cracks or divots. Another problem with the mount is that it sticks out in front of the wheels beneath the board making sharp inclines impossible to traverse. One possible solution to the this problem is to angle it up from the current position so as to get more clearance and to increase the incline angle it is able to pass over. The reason we did not do this during the semester is that it requires buying a new belt and having the mount redesigned by the machine shop, which we did not have time to do.

Other future work that can also be done to the electric longboard is implementing a nightlight/turn signal system. This had to set aside since a kill switch was need
The other future work which we wanted to implement but had to set aside in order to include the kill-switch was the LED nightlights/ turn signals that would be used for night riding. This would be fairly straightforward work but we ended up running out of time and so it was set aside until later.

8 References

[1] *Motorola Semiconductor Data Manual*, Motorola Semiconductor Products, Inc., Phoenix, AZ, 2007.

[2] *Double Data Rate (DDR) SDRAM*, datasheet, Micron Technology, Inc., 2000. Available at: http://download.micron.com/pdf/datasheets/dram/ddr/512MBDDRx4x8x16.pdf

[3] Linx Technologies LT Series, web page. Available at: http://www.linxtechnologies.com/products/rf-modules/lt-series-transceiver-modules/. Accessed January 2012.

[4] J. A. Prufrock, *Lasers and Their Applications in Surface Science and Technology*, 2nd ed. New York, NY: McGraw-Hill, 2009.

[5] W. P. Mondragon, "Principles of coherent light sources: Coherent lasers and pulsed lasers," in *Lasers and Their Applications in Surface Science and Technology*, 2nd ed., J. A. Prufrock, Ed. New York, NY: McGraw-Hill, 2009, pp. 117-132.

[6] G. Liu, "TDM and TWDM de Bruijn nets and shufflenets for optical communications," *IEEE Transactions on Computers*, vol. 59, no. 1, pp. 695-701, June 2011.

[7] S. Al Kuran, "The prospects for GaAs MESFET technology in dc–ac voltage conversion," in *Proceedings of the Fourteenth Annual Portable Design Conference*, 2010, pp. 137-142.

[8] K. E. Elliott and C. M. Greene, "A local adaptive protocol," Argonne National Laboratory, Argonne, IL, Tech. Rep. 916-1010-BB, 2006.

[9] Motorcontinua web page ‘‘ Tutorial del Motor DC,’’ available at: http://www.motoresdc.es/documentos/tutorial-motor-dc.pdf

[10] Roger Juanpere Tolrà. “ Técnicas de control para motores Brushless; Comparativa entre Conmutación Trapezoidal, Conmutación Sinusoidal y Control Vectorial’’ available at: http://www.ingeniamc.com/Es/-Control-techniques-for-brushless-motors.pdf

[11] Wayner Rademacher, tcrconline web site, last accesed in January 2008, Available at: http://www.tcrconline.com/documents/Brushless/Brushless%20Motors.pdf

[12] Stefán Baldursson, ‘‘ BLDC Motor modelling and Control,’’ Master Thesis Work, May 2005. Available at: http://webfiles.portal.chalmers.se/et/MSc/BaldurssonStefanMSc.pdf

[13] Juan Miguel García Haro, ‘‘Desarrollo de un controlador para motores DC brushless basado en CompactRIO y LabVIEW de National Instruments para el estudio de nuevos algoritmos de control,’’ November 2011. Available at: http://earchivo.uc3m.es/bitstream/handle/10016/13615/PFC_JuanMiguel_Garcia_Haro.pdf?sequence=1

[14] Fidel Fernandez Bernal, ‘‘ Principios de la máquina DC y DC Brushless,’’ Class notes for Máquinas y Accionamientos, Universidad Pontificia de Comillas, 2014

[15] Diego Langarica Córdoba, ‘‘Control de un Motor Brushless para aplicación a vehículos eléctricos,’’ Tésis de Maestria en ciencias en Ingeniería Electrónica Available at: http://www.cenidet.edu.mx/subaca/web-elec/tesis_mc/243MC_dlc.pdf

Part II.

9 Marketing Plan

9.1 Parts

Table 9.1 shows the different parts that were needed in order to build the entire modular electric longboard. As we can see in the bottom of the table, there are parts such as the box, the motor mounter, screws and other different parts that were used to attach the different parts to the longboard that were provided by the ECE shop and the cost was zero since it is a free service that University of Illinois offers for registering into ECE 445 (Senior Design Project).

Parts	Manufacturer	Retail Cost ($)	Quantity (#)	Actual Cost ($)
Longboard Deck	Carve-One	45.00	1	45.00
Galileo Gen 2	Intel	79.95	1	79.95
XBee 1mW Wire Antenna – Series 1	Digi	24.95	2	49.90
XBee Shield	SparkFun	14.95	1	14.95
XBee Explorer USB	SparkFun	24.95	2	49.90
Momentary Pushbutton Switch	SparkFun	0.50	3	1.50
50 A Switch	Pollak	6.97	1	6.97
Key Switch – Medium	SparkFun	1.95	1	1.95
Battery Holder 2xAAA	SparkFun	1.50	1	1.50
Arduino Stackable Header Kit	SparkFun	1.50	1	1.50
NTM Prop Drive Motor	HobbyKing	45.44	1	45.44
6S 10000mAh LiPo Battery Pack	Multistar	98.11	1	98.11
3S 3200 mAh LiPo Battery Pack	Venom	35.83	1	35.83
100 A ESC	HobbyKing	42.34	1	42.34
40 Tooth Gear	B&B Manufacturing	19.67	1	19.67
14 Tooth Gear	B&B Manufacturing	6.37	1	6.37

Timing Belt	B&B Manufacturing	9.75	1	9.75
83mm Wheels	Blank Pro	21.99	1	21.99
3D Printing	BIF	7.34	1	7.34
Battery Charger	iMax	35.96	1	35.96
Miscellaneous Parts	-	58.56	1	58.56
Aluminum parts	ECE shop	0.00	1	0.00
Total	**-**	**-**	**-**	**634.48**

Table 9.1 Parts cost

9.2 Labor

Table 9.2 is an estimated cost of the human labor estimated for this project being salaries estimated. Any extra hours that were needed will be charged with a different rate and has to be carefully charged with an extra cost depending on the cause of it.

Name	Hourly Rate ($)	Overhead (2.5)	Hrs./wk.	# of wks.	Total Hrs.	Total ($)
Nicholas Trivino Carver	35.00	87.50	10	11	110	9,625.00
Machine Shop	35.00	87.50	5	1	5	437.50
Total	-	-	-	-	-	**10,062.50**

Table 9.2 Labor costs

Part III.

10 Requirements and Verification

Requirement	Verification	Verification Status (Y/N)
1. Power Supply a. Battery outputs 22.2V ±2.2V.	a. Attach voltmeter across the terminals of the battery and check that it gives between 20.0V and 24.4V.	Y
2. Microcontroller a. Check that 11.1 ±0.555V is provided to the Arduino. b. 3.3V ±10% is supplied to XBee c. Outputs correct PWM signal based on desire speed.	a. Connect voltmeter across the terminals of the Arduino and check that it is between 10.545V and 11.655V. b. Use voltage divider to test leads going into the XBee c. Test the voltage output from the controller under different speed cases.	Y
3. Motor Controller a. Changes the voltage proportionally to the input received from the microcontroller.	a. Test the voltage output from the motor controller under different outputs from the microcontroller.	Y
4. Motor a. Motor should provide at least 1.5 Nm of torque.	a. Connect ammeter to motor to find current, compute power then find torque using power and speed.	Y
5. Drivetrain a. Rotates at 4650 RPM ±46.5 RPM.	a. Check that the RPM of the wheel is between 4603.5 RPM and 4696.5 RPM.	Y

6. Wireless Receiver a. Communication range of 100 feet ±10 feet (2.4GHz) b. Correct data is received from controller	a. Test communication range between XBees b. Connect to Arduino and check signals received when values are input from the controller.	Y
7. Wireless Controller a. Outputs proper signal to XBee controller mounted on the Arduino.	a. Check signal received by XBee mounted on the Arduino when input is sent from the controller.	Y
8. Controller Battery a. Provides proper voltage for the controller.	a. Attach voltmeter across terminals of the battery and check the voltage.	Y

Table 10.1 Requirements and Verifications

Part IV.

Award

ECE 445 Hall of Fame

Area Award: Transportation

Team 13 - "Modular Electric Longboard"

Dillon Cunningham, Jordan Johnson, Nicholas Trivino Carver

******Spring 2015******

P. Scott Carney, Professor

Michael Oelze, Associate Professor

Ben Cahill, Teaching Assistant

William H. Sanders, Department Head

Part V.

Datasheets

FOR 9 mm BELTS (.354 INCH)
MOLDED
SINGLE FLANGE
TRUE METRIC® PROFILE

Inch
0 1

› MATERIAL:
Polycarbonate, Fiberglass Reinforced

› SPECIFICATION:
Pulleys with 11 to 19 grooves do not have webs.

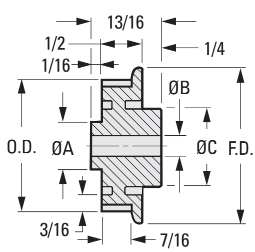


Fig. 1

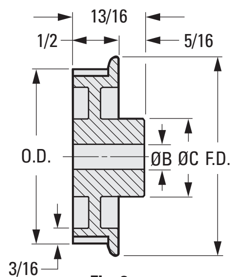
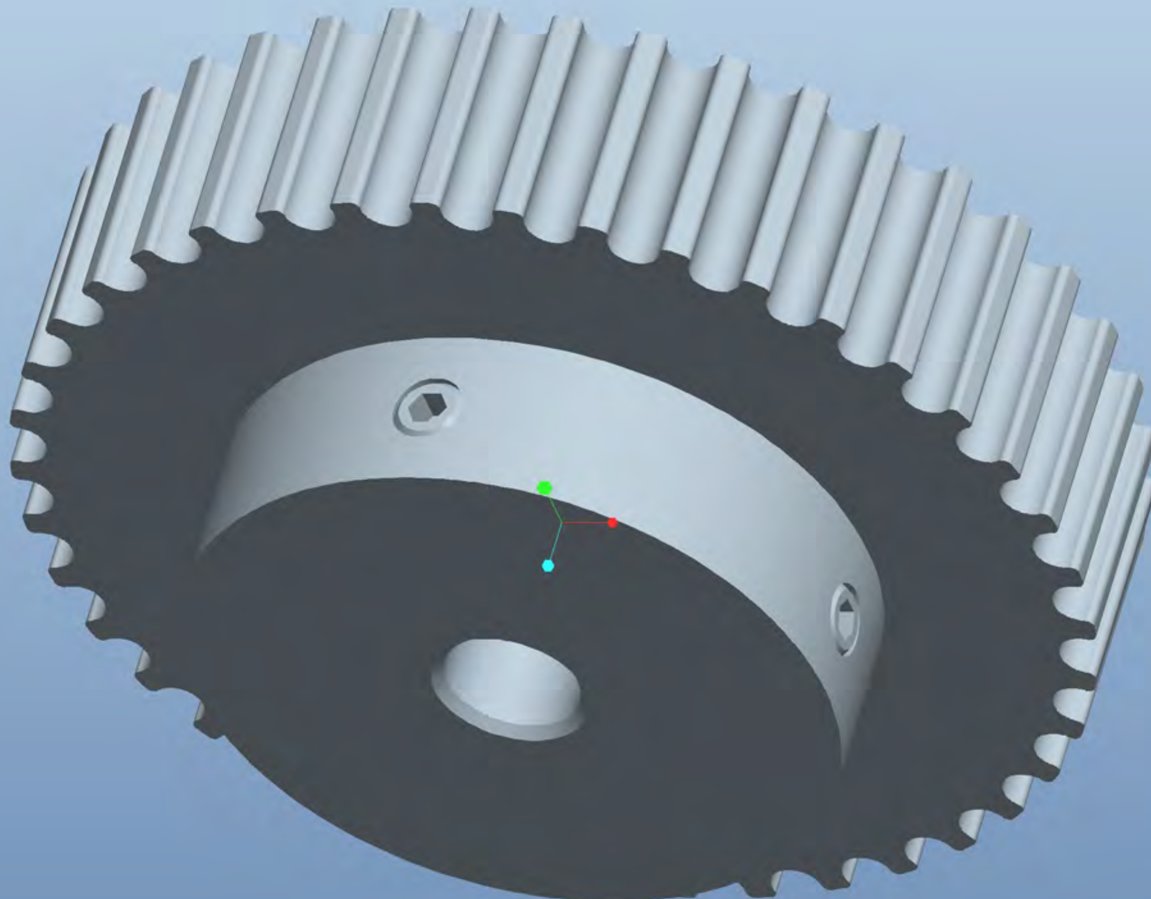


Fig. 2

INCH COMPONENT

Catalog Number	No. of Grooves	P.D.	O.D.	F.D.	B Bore +.001 -.000	A Dia.	C Hub Dia.
Fig. 1							
A 6L25-011SF0906	11	.689	.644	.87	.1875	3/8	11/16
A 6L25-012SF0906	12	.752	.707	.93			
A 6L25-013SF0906	13	.815	.770	.99			
A 6L25-014SF0906	14	.877	.832	1.06			
A 6L25-015SF0908	15	.940	.895	1.19	.250	1/2	3/4
A 6L25-016SF0908	16	1.003	.958				
A 6L25-017SF0908	17	1.065	1.020	1.24			
A 6L25-018SF0908	18	1.128	1.083	1.31			
A 6L25-019SF0908	19	1.191	1.146	1.38			
A 6L25-020SF0908	20	1.253	1.208	1.44			
A 6L25-022SF0908	22	1.379	1.334	1.57			7/8
A 6L25-025SF0908	25	1.566	1.521	1.76			
A 6L25-028SF0908	28	1.754	1.709	1.95			
A 6L25-029SF0908	29	1.817	1.772	2.02			
A 6L25-030SF0908	30	1.880	1.835	2.08			
Fig. 2							
A 6L25-040SF0910	40	2.506	2.461	2.71	.3125	—	7/8
A 6L25-050SF0910	50	3.133	3.088	3.29			

Rev: 9.11.13 JC



SDP/SI
PHONE: 516.328.3300 • FAX: 516.326.8827 • WWW.SDP-SI.COM

FOR 9 mm BELTS
DOUBLE FLANGE
TRUE METRIC® PROFILE

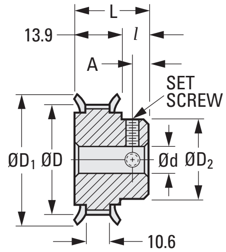
Metric
0 10

› MATERIAL:
Aluminum Alloy

› FINISH:
Clear Anodized

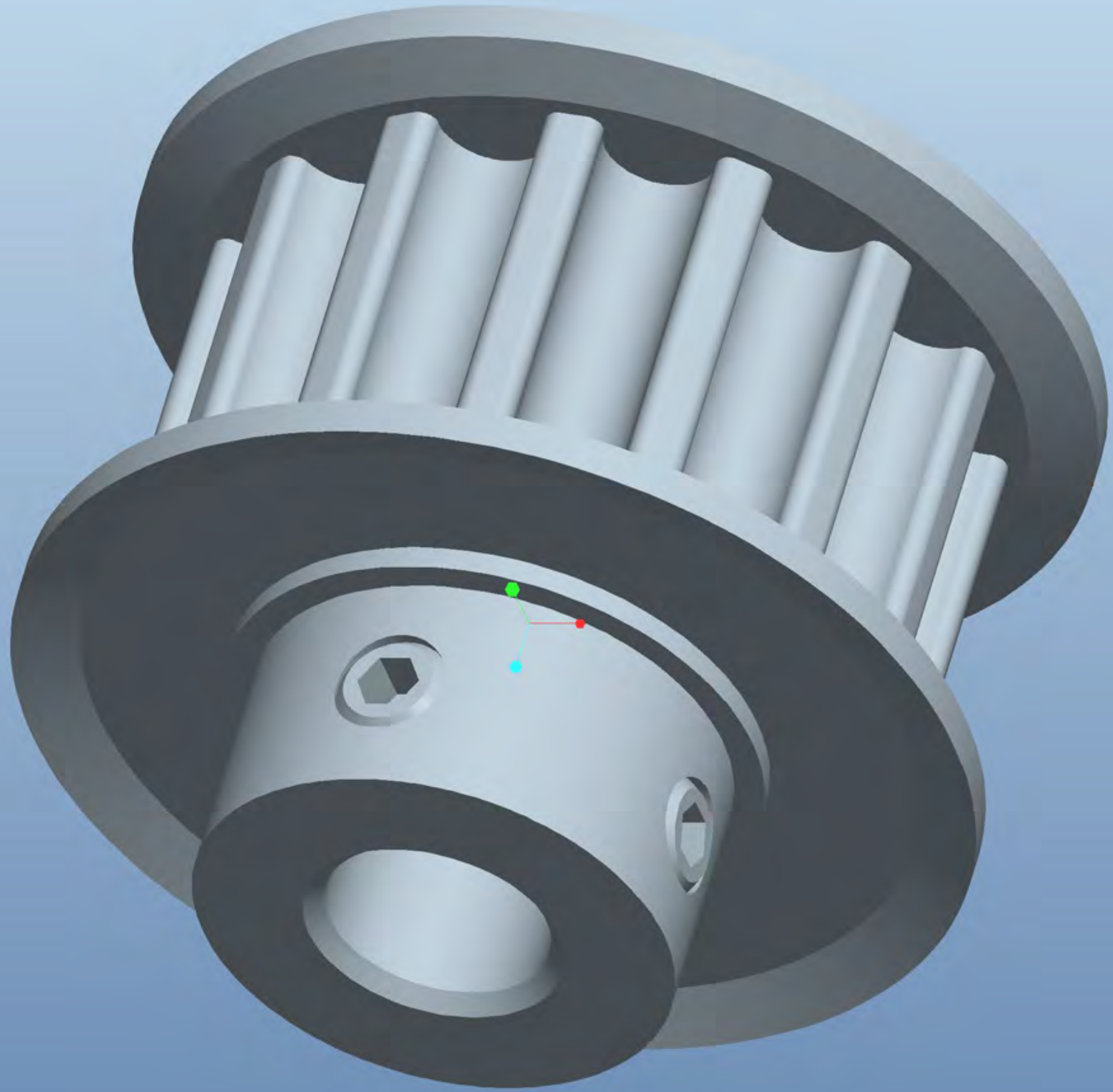
› SPECIFICATIONS:
D Tolerance: 2 to 16 grooves is +0.05/0
17 to 32 grooves is +0.08/0
34 grooves is +0.10/0

Pulleys with 12 and 13 grooves have 1 set screw; others have 2 set screws at 90°.



METRIC COMPONENT

Catalog Number	No. of Grooves	P.D.	D Dia.	D_1 Dia. ± 0.4	d Bore +0.025 0	L Length ± 0.4	D_2 Hub Dia. ± 0.4	l Hub Proj.	A	Set Screw
A 6A25M012DF0906	12	19.1	18	22.2	6	20.2	11.1	6.3	3.2	M3
A 6A25M013DF0906	13	20.7	19.6	23.8	6	20.2	12.7	6.3	3.2	M3
A 6A25M014DF0906	14	22.2	21.1	25.4	6	20.2	12.7	6.3	3.2	M3
A 6A25M015DF0906	15	23.8	22.7	27	6	20.2	14.3	6.3	3.2	M3
A 6A25M016DF0906	16	25.4	24.3	27.8	6	20.2	14.3	6.3	3.2	M3
A 6A25M017DF0908	17	27	25.9	30.2	8	20.2	15.9	6.3	3.2	M4
A 6A25M018DF0908	18	28.6	27.5	31.8	8	20.2	17.5	6.3	3.2	M4
A 6A25M019DF0908	19	30.2	29.1	33.3	8	20.2	19.1	6.3	3.2	M4
A 6A25M020DF0908	20	31.8	30.7	34.9	8	20.2	20.6	6.3	3.2	M4
A 6A25M022DF0908	22	35	33.9	38.1	8	20.2	23.8	6.3	3.2	M4
A 6A25M024DF0908	24	38.2	37.1	41.3	8	21.8	25.4	7.9	4	M4
A 6A25M025DF0908	25	39.8	38.7	42.9	8	21.8	25.4	7.9	4	M4
A 6A25M026DF0908	26	41.4	40.2	44.5	8	21.8	27	7.9	4	M4
A 6A25M028DF0908	28	44.5	43.4	47.6	8	21.8	30.2	7.9	4	M4
A 6A25M030DF0908	30	47.8	46.6	50.8	8	21.8	30.2	7.9	4	M4
A 6A25M032DF0908	32	50.9	49.8	54	8	21.8	31.8	7.9	4	M4
A 6A25M034DF0908	34	54.1	53	57.2	8	21.8	35	7.9	4	M4



BELT WIDTHS
METRIC - 6, 9, 15 & 25 mm
TRUE METRIC® PROFILE

Metric
0 10

❯ MATERIAL:

Nylon Covered, Fiberglass Reinforced, Neoprene

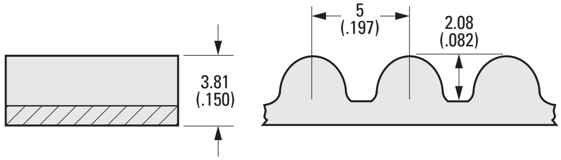
❯ SPECIFICATIONS:

Breaking Strength:
316 N per 1 mm (226 lbf per 1/8 in.) Belt Width; not representative of the load-carrying capacity of the belt.
Working Tension:
454 N for 25.4 mm belt (102 lbf for 1 in. belt).
For more information, see the technical section.
Temperature Range:
-34°C to +85°C (-30°F to +185°F)

❯ MODIFICATIONS:

Special Widths - cut to size from sleeves available from stock.

Pulleys are available with metric or inch standards.



NOTE: Dimensions in ( ) are inch.

METRIC COMPONENT CATALOG NUMBER

A 6R25M□□□□□□

No. of Grooves Code

Belt Width mm	Width Code
6 (.236)	**060**
9 (.354)	**090**
15 (.591)	**150**
25 (.984)	**250**

Groove Code	Pitch Length mm	Pitch Length Inch
024	120	4.724
035	175	6.890
036	180	7.087
038	190	7.480
040	200	7.874
043	215	8.465
045	225	8.858
046	230	9.055
048	240	9.449
049	245	9.646
051	255	10.039
052	260	10.236
053	265	10.433
054	270	10.630
055	275	10.827
056	280	11.024
057	285	11.220
059	295	11.614
060	300	11.811
061	305	12.008
062	310	12.205
064	320	12.598
065	325	12.795
066	330	12.992
067	335	13.189
068	340	13.386

Groove Code	Pitch Length mm	Pitch Length Inch
069	345	13.583
070	350	13.780
072	360	14.173
073	365	14.370
074	370	14.567
075	375	14.764
077	385	15.157
080	400	15.748
081	405	15.945
082	410	16.142
083	415	16.339
084	420	16.535
085	425	16.732
090	450	17.717
092	460	18.110
093	465	18.307
095	475	18.701
096	480	18.898
099	495	19.488
100	500	19.685
104	520	20.472
105	525	20.669
107	535	21.063
110	550	21.654
111	555	21.850
112	560	22.047

Continued on the next page

PHONE: 516.328.3300 • FAX: 516.326.8827 • WWW.SDP-SI.COM

Metric
0 10

METRIC COMPONENT CATALOG NUMBER

A 6 R 2 5 M □□□□□□

No. of Grooves Code

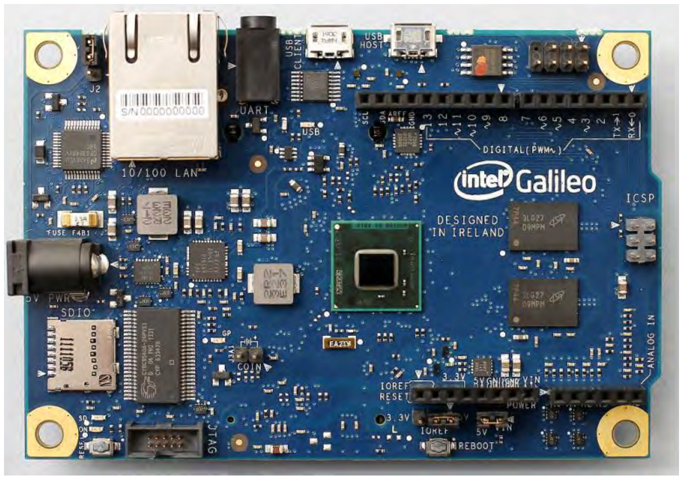
Belt Width mm	Width Code
6 (.236)	**060**
9 (.354)	**090**
15 (.591)	**150**
25 (.984)	**250**

Groove Code	Pitch Length	
	mm	Inch
113	565	22.244
115	575	22.638
116	580	22.835
117	585	23.031
118	590	23.228
120	600	23.622
122	610	24.016
123	615	24.213
124	620	24.409
125	625	24.606
127	635	25.000
128	640	25.197
129	645	25.394
131	655	25.787
133	665	26.181
134	670	26.378
136	680	26.772
137	685	26.968
139	695	27.362
140	700	27.559
142	710	27.953
144	720	28.346
148	740	29.134
149	745	29.331
150	750	29.528
151	755	29.724
153	765	30.118
154	770	30.315
155	775	30.512
158	790	31.102
160	800	31.496
162	810	31.890
165	825	32.480
166	830	32.677
167	835	32.874
169	845	33.268
170	850	33.465
172	860	33.858
174	870	34.252
178	890	35.039
180	900	35.433
184	920	36.220
185	925	36.417
186	930	36.614
187	935	36.811
188	940	37.008
190	950	37.402
193	965	37.992
195	975	38.386
196	980	38.583

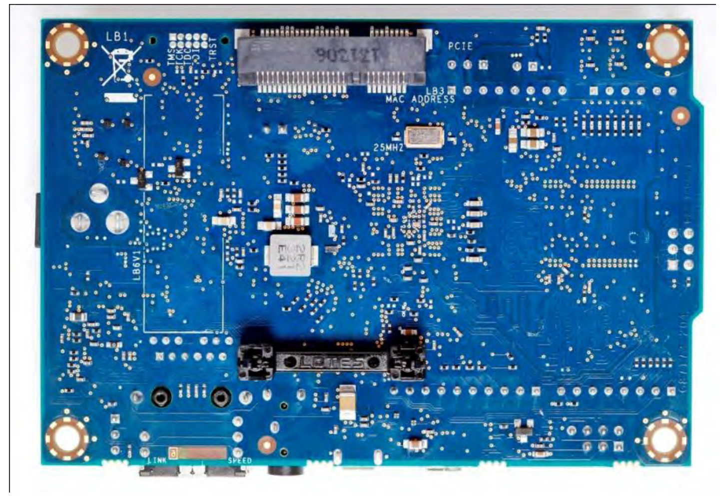
Groove Code	Pitch Length	
	mm	Inch
197	985	38.779
200	1000	39.370
205	1025	40.354
207	1035	40.748
208	1040	40.945
210	1050	41.339
220	1100	43.307
223	1115	43.898
225	1125	44.291
227	1135	44.685
229	1145	45.079
235	1175	46.260
239	1195	47.047
240	1200	47.244
245	1225	48.228
247	1235	48.622
250	1250	49.213
254	1270	50.000
259	1295	50.984
270	1350	53.150
275	1375	54.134
276	1380	54.331
284	1420	55.905
300	1500	59.055
304	1520	59.843
315	1575	62.008
319	1595	62.795
327	1635	64.370
338	1690	66.535
344	1720	67.716
358	1790	70.472
360	1800	70.866
374	1870	73.622
379	1895	74.606
389	1945	76.575
396	1980	77.953
400	2000	78.740
420	2100	82.677
422	2110	83.071
450	2250	88.583
470	2350	92.520
505	2525	99.409
552	2760	108.661
624	3120	122.834
634	3170	124.803
640	3200	125.984
686	3430	135.039
760	3800	149.606
800	4000	157.480

Continued from the previous page

Galileo Datasheet



Galileo Front



Galileo Back

Overview

Galileo is a microcontroller board based on the Intel® Quark SoC X1000 Application Processor, a 32-bit Intel Pentium-class system on a chip (datasheet). It is the first board based on Intel® architecture designed to be hardware and software pin-compatible with Arduino shields designed for the Uno R3. Digital pins 0 to 13 (and the adjacent AREF and GND pins), Analog inputs 0 to 5, the power header, ICSP header, and the UART port pins (0 and 1), are all in the same locations as on the Arduino Uno R3. This is also known as the Arduino 1.0 pinout.

Order Number: 329681-003US

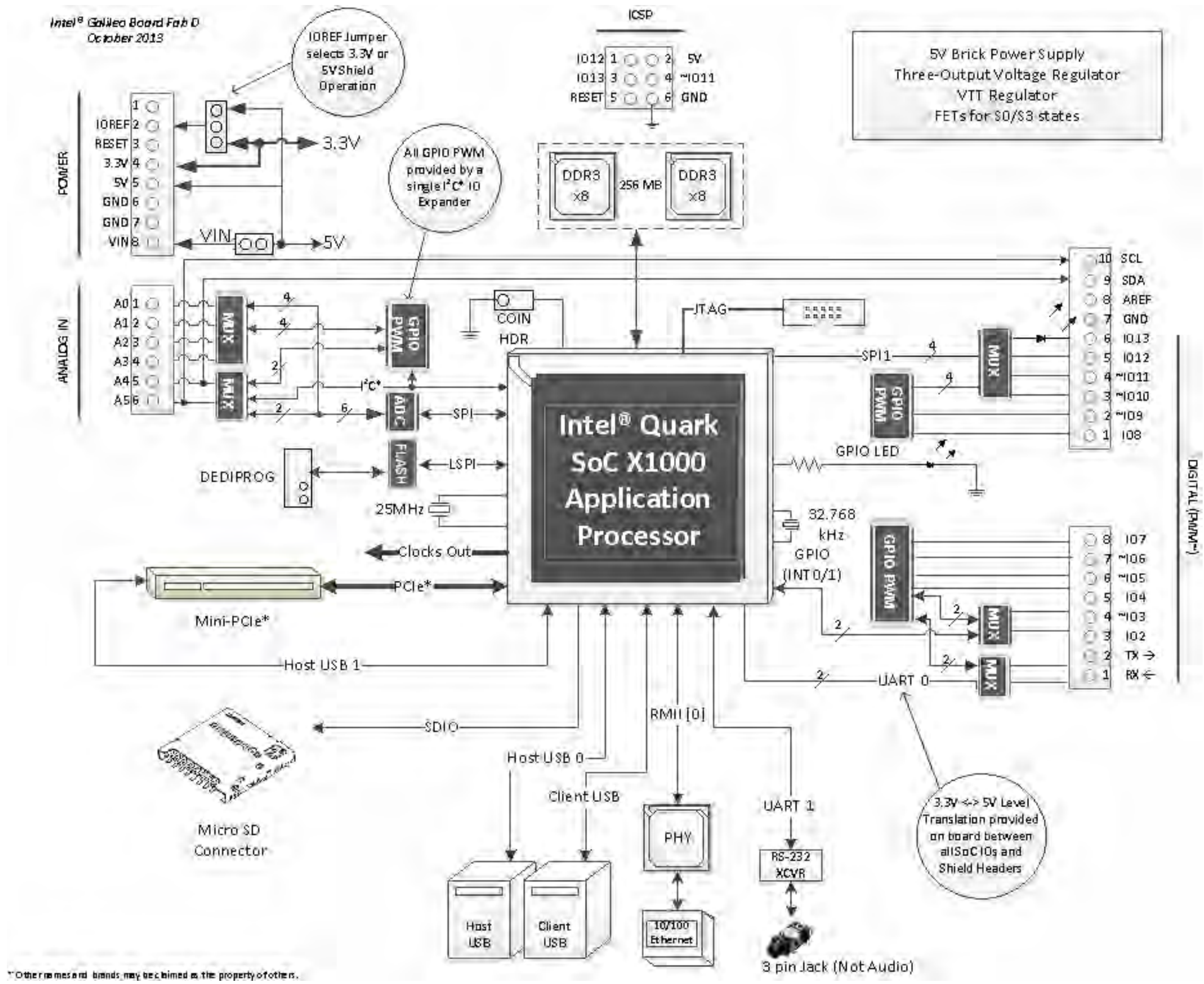
Galileo is designed to support shields that operate at either 3.3V or 5V. The core operating voltage of Galileo is 3.3V. However, a jumper on the board enables voltage translation to 5V at the I/O pins. This provides support for 5V Uno shields and is the default behavior. By switching the jumper position, the voltage translation can be disabled to provide 3.3V operation at the I/O pins.

Of course, the Galileo board is also SW compatible with the Arduino SW Development Environment, which makes usability and introduction a snap.

In addition to Arduino HW and SW compatibility, the Galileo board has several PC industry standard I/O ports and features to expand native usage and capabilities beyond the Arduino shield ecosystem. A full sized mini-PCI Express* slot, 100Mb Ethernet port, Micro-SD slot, RS-232 serial port, USB Host port, USB Client port, and 8MByte NOR flash come standard on the board.

Order Number: 329681-003US

intel® Galileo



Order Number: 329681-003US

Getting Started

To get started, simply connect the board to power with the 5V AC-to-DC adapter and then connect to the computer with the micro-USB cable.

Galileo has a dedicated forum for discussing the board.

Details and Specifications

Arduino Shield Supported Features

Galileo is compatible with Arduino Uno shields and is designed to support 3.3V or 5V shields, following the Arduino Uno Revision 3, including:

- **14 digital input/output pins,** of which 6 can be used as Pulse Width Modulation (PWM) outputs;
    - Each of the 14 digital pins on Galileo can be used as an input or output, using pinMode(), digitalWrite(), and digitalRead() functions.
    - The pins operate at 3.3 volts or 5 volts. Each pin can source a max of 10mA or sink a maximum of 25 mA and has an internal pull-up resistor (disconnected by default) of 5.6k to 10 kOhms.
- **A0 – A5 -** 6 analog inputs, via an AD7298 analog-to-digital (A/D) converter (datasheet)
    - Each of the 6 analog inputs, labeled A0 through A5, provides 12 bits of resolution (i.e., 4096 different values). By default they measure from ground to 5 volts.
- **I^2C* bus, TWI,** with SDA and SCL pins that are near to the AREF pin.
    - TWI: A4 or SDA pin and A5 or SCL pin. Support TWI communication using the Wire library.
- **SPI**
    - Defaults to 4MHz to support Arduino Uno shields. Programmable up to 25MHz.

    - **Note:** While Galileo has a native SPI controller, it will act as a master and not as an SPI slave. Therefore, Galileo cannot be a SPI slave to another SPI master. It can act, however, as a slave device via the USB Client connector.
- **UART** (serial port) Programmable speed UART port (Pins 0 (RX) and 1 (TX))
- **ICSP (SPI) -** a 6 pin in-circuit serial programming (ICSP) header, located appropriately to plug into existing shields. These pins support SPI communication using the SPI library.
- **VIN.** The input voltage to the Galileo board when it's using an external power source (as opposed to 5 volts from the regulated power supply connected at the power jack). You can supply voltage through this pin, or, if supplying voltage via the power jack, access it through this pin.
    - **Warning:** The voltage applied to this pin must be a regulated 5V supply otherwise it could damage the Galileo board or cause incorrect operation.
- **5V output pin.** This pin outputs 5V from the external source or the USB connector. Maximum current draw to the shield is 800 mA
- **3.3V output pin.** A 3.3 volt supply generated by the on-board regulator. Maximum current draw to the shield is 800 mA
- **GND.** Ground pins.
- **IOREF.** The IOREF pin on Galileo allows an attached shield with the proper configuration to adapt to the voltage provided by the board. The IOREF pin voltage is controlled by a jumper on the board, i.e., a selection jumper on the board is used to select between 3.3V and 5V shield operation.
- **RESET** button/pin
    - Bring this line LOW to reset the sketch. Typically used to add a reset button to shields that block the one on the board.
- **AREF** is unused on Galileo. Providing an external reference voltage for the analog inputs is not supported.
    - For Galileo it is not possible to change the upper end of the analog input range using the AREF pin and the analogReference() function.

Details of Intel® Architecture Supported Features

The genuine Intel processor and surrounding native I/O capabilities of the SoC provides for a fully featured offering for both the maker community and students alike. It will also be useful to professional developers who are looking for a more simple and cost effective development environment to the more complex Intel® Atom processor and Intel® Core processor-based designs.

- 400MHz 32-bit Intel® Pentium instruction set architecture (ISA)-compatible processor
  - 16 KByte L1 cache
  - 512 KBytes of on-die embedded SRAM
  - Simple to program: Single thread, single core, constant speed
  - ACPI compatible CPU sleep states supported
  - An integrated Real Time Clock (RTC), with an optional 3V "coin cell" battery for operation between turn on cycles.
- 10/100 Ethernet connector
- Full PCI Express* mini-card slot, with PCIe* 2.0 compliant features
  - Works with half mini-PCIe* cards with optional converter plate
  - Provides USB 2.0 Host Port at mini-PCIe* connector
- USB 2.0 Host connector
  - Support up to 128 USB end point devices
- USB Client connector, used for programming
  - Beyond just a programming port - a fully compliant USB 2.0 Device controller
- 10-pin Standard JTAG header for debugging
- Reboot button to reboot the processor
- Reset button to reset the sketch and any attached shields
- Storage options:
  - 8 MByte Legacy SPI Flash whose main purpose is to store the firmware (or bootloader) and the latest sketch. Between 256 KByte and 512 KByte is dedicated for sketch storage. The upload happens automatically from the development PC, so no action is required unless there is an upgrade that is being added to the firmware.

- 512 KByte embedded SRAM that is enabled by the firmware by default.
- 256 MByte DRAM, enabled by the firmware by default.
- Optional micro SD card offers up to 32GByte of storage
- USB storage works with any USB 2.0 compatible drive
- 11 KByte EEPROM can be programmed via the EEPROM library.

Schematic, Reference Design & Pin Mapping

- Schematic: Galileo-schematic.pdf
- Cadence® Allegro® files: Galileo-reference-design.zip

Power

Galileo is powered via an AC-to-DC adapter, connected by plugging a 2.1mm center-positive plug into the board's power jack. The recommended output rating of the power adapter is 5V at up to 3A.

Electrical Summary

Input Voltage (recommended)	5V
Input Voltage (limits)	5V
Digital I/O Pins	14 (of which 6 provide PWM output)
Analog Input Pins	6
Total DC Output Current on all I/O lines	80 mA
DC Current for 3.3V Pin	800 mA
DC Current for 5V Pin	800 mA

Communication

Galileo has a number of facilities for communicating with a computer, another Arduino, or other microcontrollers.

Galileo provides **UART** TTL (5V/3.3V) serial communication, which is available on digital pin 0 (RX) and 1 (TX). In addition, a second UART provides RS-232 support and is connected via a 3.5mm jack.

The **USB Client** ports allows for serial (CDC-ACM) communications over USB. This provides a serial connection to the Serial Monitor or other applications on your computer. It is also used to upload sketches to the board.

The **USB Host** port allows Galileo act as a USB Host for connected peripherals such as mice, keyboards, and smartphones. To use these features, see the USBHost reference pages.

Galileo is the first Arduino board to provide a mini **PCI Express*** (mPCIe*) slot. This slot allows full size and half size (with adapter) mPCIe* modules to be connected to the board and also provides an additional USB Host port via the mPCIe* slot. Any standard mPCIe* module can be connected and used to provide applications such as WiFi, Bluetooth or Cellular connectivity. Initially, the Galileo mPCie* slot provides support for the WiFi Library. For additional information, see the Intel® Galileo Getting Started Guide.

An **Ethernet RJ45 Connector** is provided to allow Galileo to connect to wired networks. Full support of on-board Ethernet interface is fully supported and does not require the use of the SPI interface like existing Arduino shields.

The onboard **microSD** card reader is accessible through the SD Library. The communication between Galileo and the SD card is provided by an integrated SD controller and does not require the use of the SPI interface like other Arduino boards. The native SD interface runs at up to 50MHz depending on the class of card used.

The Arduino software includes a Wire library to simplify use of the **TWI/I^{2}C*** bus; see the documentation for details.

For **SPI** communication, use the SPI library.

Programming

Galileo can be programmed with the Arduino software (download). When you are ready to upload the sketch to the board, program Galileo through the USB Client port by selecting "Intel Galileo" as your board in the Arduino IDE. Connect Galileo's port labelled USB Client (the one closest to the Ethernet) to your computer.
For details, see the reference, tutorials and Intel® Galileo Getting Started Guide.

Rather than requiring a physical press of the reset button before an upload, Galileo is designed to be reset by software running on a connected computer.

When the board boots up two scenarios are possible:

- If a sketch is present in persistent storage, it is executed.
- If no sketch present, the board waits for upload commands from the IDE.

If a sketch is executing, you can upload from the IDE without having to press the reset button on the board. The sketch is stopped; the IDE waits for the upload state, and then starts the newly uploaded sketch.

Pressing the reset button on the board restarts a sketch if it is executing and resets any attached shields.

Properties of Pins Configured as OUTPUT

Pins configured as OUTPUT with pinMode() are said to be in a low-impedance state. On Galileo, when a pin is configured as OUTPUT, the functionality is provided via an I^2C*-based Cypress I/O expander (datasheet). Digital pins 0 to 13 and Analog pins A0 to A5 can be configured as OUTPUT pins on Galileo.

The I/O expander's pins, when configured as OUTPUT, can source (provide positive current) up to 10 mA (milliamps) and can sink (provide negative current) up to 25 mA of current to other devices/circuits. The individual per pin current sourcing capability of 10 mA is subject to an overall limit of 80 mA combined between all OUTPUT pins. The per pin capability current sinking capability is subject to an overall limit of 200 mA. The following table provides a breakdown of the overall OUTPUT capabilities of the pins.

	Current Source (mA)	Current Sink (mA)
Per Pin Capability	10	25
Digital Pins 3,5,9,10,12, 13 Combined	40	100
Digital Pins 0,1,2,4,6,7,8,11 and Analog Pins A0,A1,A2,A3,A4, A5 Combined	40	100
Digital Pins 0-13 and Analog Pins A0-A5 Combined	80	200

Galileo Jumper Configuration

There are three jumpers on Galileo that are used to vary the configuration of the board.

IOREF Jumper

To allow Galileo support both 3.3V and 5V shields, the external operating voltage is controlled via a jumper. When the jumper is connected to 5V, Galileo is configured to be compatible with 5V shields and IOREF is set to 5V. When the jumper is connected 3.3V, Galileo is configured to be compatible with 3.3V shields and IOREF is set to 3.3V.

The input range of the Analog pins is also controlled by the IOREF jumper and must not exceed the chosen operating voltage. However, the resolution of AnalogRead() remains at 5 V/1024 units for the default 10-bit resolution or, 0.0049V (4.9mV) per unit regardless of IOREF jumper setting.

Warning: The IOREF jumper should be used to match the board and shield operating voltages. Incorrectly setting the voltage could damage the board or the shield.

I^2C* Address Jumper

To prevent a clash between the I^2C* Slave address of the on board I/O expander and EEPROM with any external I^2C Slave devices, jumper J2 can be used to vary the I^2C* address of the on-board devices.

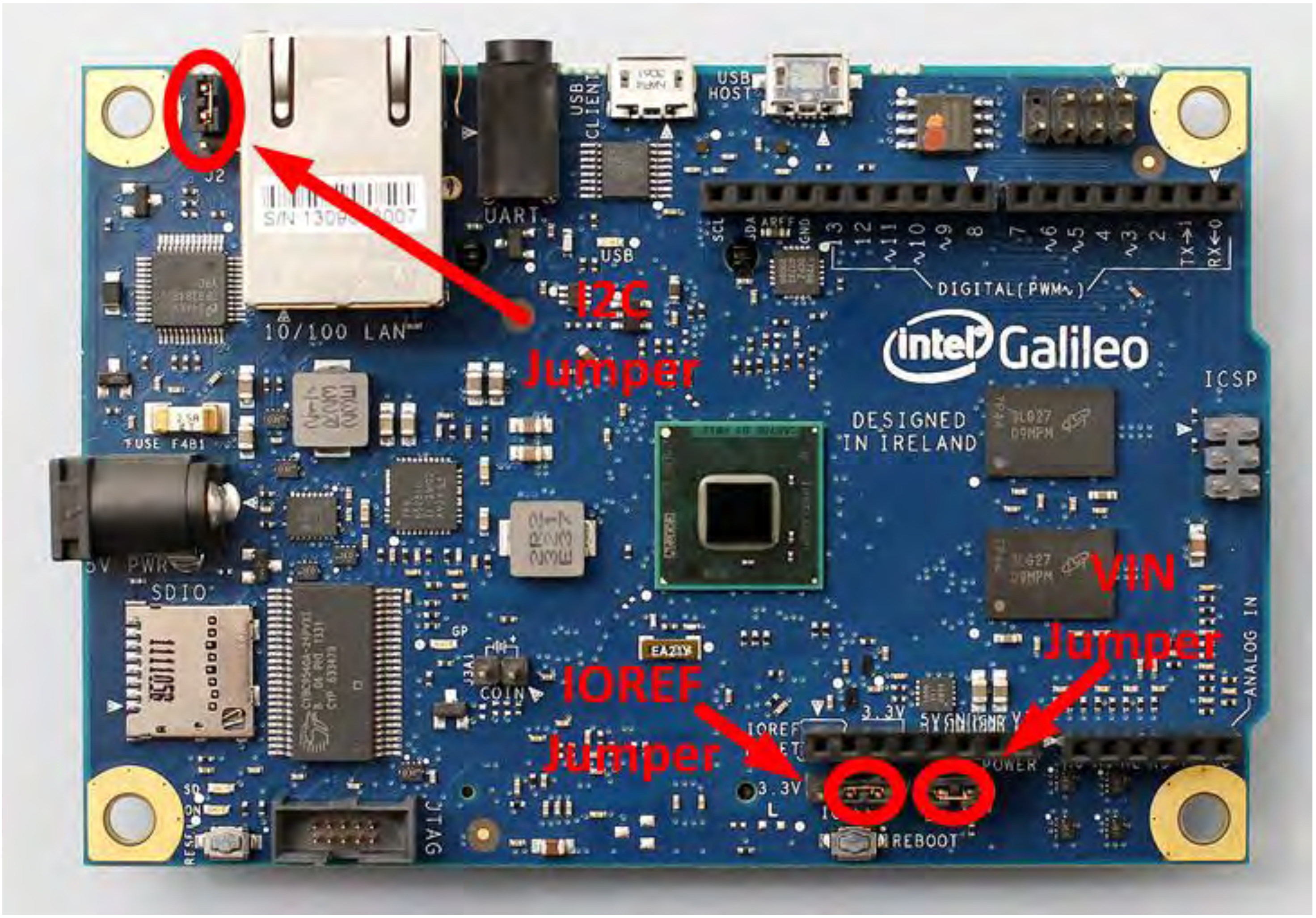
With J2 connected to pin 1 (marked with white triangle), the 7-bit I/O Expander address is 0100001 and the 7-bit EEPROM address is 1010001. Changing the jumper position changes the I/O Expander address to 0100000 and the EEPROM address to 1010000.

VIN Jumper

On Galileo, the VIN pin can be used to supply 5V from the regulated power supply connected at the power jack to attached shields or devices. If there is a need to supply more than 5V to a shield using VIN then the VIN jumper should be removed from Galileo to break the connection between the on-board 5V supply and the VIN connection on the board header.

Warning: If the VIN jumper is not removed and more than 5V is connected to VIN, it may damage the board or lead to unreliable operation.

Order Number: 329681-003US



Order Number: 329681-003US

Automatic (Software) Reset

Rather than requiring a physical press of the reset button before an upload, Galileo is designed in a way that allows it to be reset by software running on a connected computer. USB CDC-ACM control signals are used to transition Galileo from run-time to bootloader mode. The Arduino software uses this capability to allow you to upload code by simply pressing the upload button in the Arduino environment. For details, see the Intel® Galileo Getting Started Guide.

Physical Characteristics

Galileo is 4.2 inches long and 2.8 inches wide respectively, with the USB connectors, UART jack, Ethernet connector, and power jack extending beyond the former dimension. Four screw holes allow the board to be attached to a surface or case. Note that the distance between digital pins 7 and 8 is 160 mil (0.16"), is not an even multiple of the 100 mil spacing of the other pins.

Intel® Galileo Design Document

07 Oct 2013

1. XBee®/XBee-PRO® RF Modules

The XBee and XBee-PRO RF Modules were engineered to meet IEEE 802.15.4 standards and support the unique needs of low-cost, low-power wireless sensor networks. The modules require minimal power and provide reliable delivery of data between devices.

The modules operate within the ISM 2.4 GHz frequency band and are pin-for-pin compatible with each other.

Key Features

Long Range Data Integrity

XBee

- Indoor/Urban: up to 100’ (30 m)
- Outdoor line-of-sight: up to 300’ (90 m)
- Transmit Power: 1 mW (0 dBm)
- Receiver Sensitivity: -92 dBm

XBee-PRO

- Indoor/Urban: up to 300’ (90 m), 200' (60 m) for International variant
- Outdoor line-of-sight: up to 1 mile (1600 m), 2500' (750 m) for International variant
- Transmit Power: 63mW (18dBm), 10mW (10dBm) for International variant
- Receiver Sensitivity: -100 dBm

RF Data Rate: 250,000 bps

Advanced Networking & Security

Retries and Acknowledgements

DSSS (Direct Sequence Spread Spectrum)

Each direct sequence channels has over 65,000 unique network addresses available

Source/Destination Addressing

Unicast & Broadcast Communications

Point-to-point, point-to-multipoint and peer-to-peer topologies supported

Low Power

XBee

- TX Peak Current: 45 mA (@3.3 V)
- RX Current: 50 mA (@3.3 V)
- Power-down Current: < 10 µA

XBee-PRO

- TX Peak Current: 250mA (150mA for international variant)
- TX Peak Current (RPSMA module only): 340mA (180mA for international varian
- RX Current: 55 mA (@3.3 V)
- Power-down Current: < 10 µA

ADC and I/O line support

Analog-to-digital conversion, Digital I/O

I/O Line Passing

Easy-to-Use

No configuration necessary for out-of box RF communications

Free X-CTU Software
(Testing and configuration software)

AT and API Command Modes for configuring module parameters

Extensive command set

Small form factor

Worldwide Acceptance

FCC Approval (USA) Refer to Appendix A [p64] for FCC Requirements.
Systems that contain XBee®/XBee-PRO® RF Modules inherit Digi Certifications.

ISM (Industrial, Scientific & Medical) **2.4 GHz frequency band**

Manufactured under **ISO 9001:2000** registered standards

XBee®/XBee-PRO® RF Modules are optimized for use in the United States, Canada, Australia, Japan, and Europe. Contact Digi for complete list of government agency approvals.

Specifications

Table 1-01. Specifications of the XBee®/XBee-PRO® RF Modules

Specification	XBee	XBee-PRO
Performance		
Indoor/Urban Range	Up to 100 ft (30 m)	Up to 300 ft. (90 m), up to 200 ft (60 m) International variant
Outdoor RF line-of-sight Range	Up to 300 ft (90 m)	Up to 1 mile (1600 m), up to 2500 ft (750 m) international variant
Transmit Power Output (software selectable)	1mW (0 dBm)	63mW (18dBm)* 10mW (10 dBm) for International variant
RF Data Rate	250,000 bps	250,000 bps
Serial Interface Data Rate (software selectable)	1200 bps - 250 kbps (non-standard baud rates also supported)	1200 bps - 250 kbps (non-standard baud rates also supported)
Receiver Sensitivity	-92 dBm (1% packet error rate)	-100 dBm (1% packet error rate)
Power Requirements		
Supply Voltage	2.8 – 3.4 V	2.8 – 3.4 V
Transmit Current (typical)	45mA (@ 3.3 V)	250mA (@3.3 V) (150mA for international variant) RPSMA module only: 340mA (@3.3 V) (180mA for international variant)
Idle / Receive Current (typical)	50mA (@ 3.3 V)	55mA (@ 3.3 V)
Power-down Current	< 10 µA	< 10 µA
General		
Operating Frequency	ISM 2.4 GHz	ISM 2.4 GHz
Dimensions	0.960” x 1.087” (2.438cm x 2.761cm)	0.960” x 1.297” (2.438cm x 3.294cm)
Operating Temperature	-40 to 85º C (industrial)	-40 to 85º C (industrial)
Antenna Options	Integrated Whip, Chip or U.FL Connector, RPSMA Connector	Integrated Whip, Chip or U.FL Connector, RPSMA Connector
Networking & Security		
Supported Network Topologies	Point-to-point, Point-to-multipoint & Peer-to-peer	
Number of Channels (software selectable)	16 Direct Sequence Channels	12 Direct Sequence Channels
Addressing Options	PAN ID, Channel and Addresses	PAN ID, Channel and Addresses
Agency Approvals		
United States (FCC Part 15.247)	OUR-XBEE	OUR-XBEEPRO
Industry Canada (IC)	4214A XBEE	4214A XBEEPRO
Europe (CE)	ETSI	ETSI (Max. 10 dBm transmit power output)*
Japan	R201WW07215214	R201WW08215111 (Max. 10 dBm transmit power output)*
Austraila	C-Tick	C-Tick

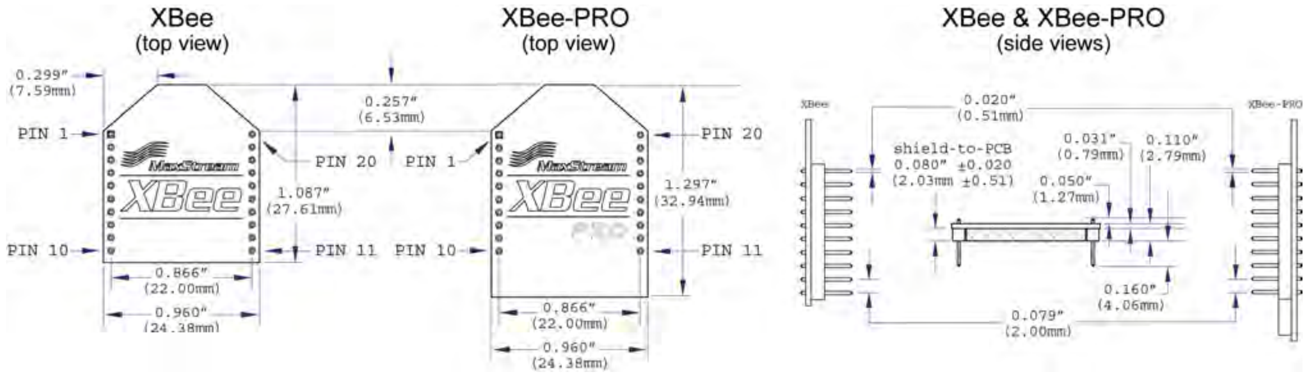
* See Appendix A for region-specific certification requirements.

Antenna Options: The ranges specified are typical when using the integrated Whip (1.5 dBi) and Dipole (2.1 dBi) antennas. The Chip antenna option provides advantages in its form factor; however, it typically yields shorter range than the Whip and Dipole antenna options when transmitting outdoors.For more information, refer to the "XBee Antennas" Knowledgebase Article located on Digi's Support Web site

Mechanical Drawings

Figure 1-01. Mechanical drawings of the XBee®/XBee-PRO® RF Modules (antenna options not shown)

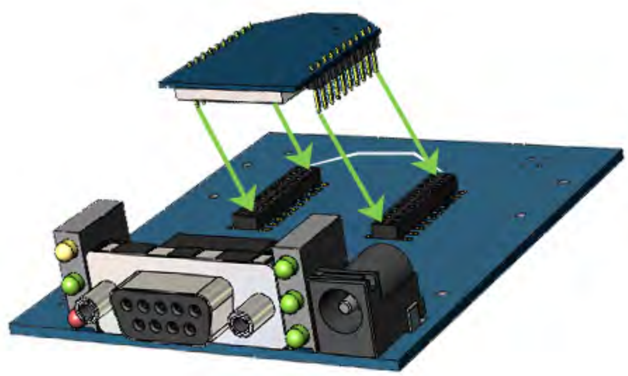
The XBee and XBee-PRO RF Modules are pin-for-pin compatible.



Mounting Considerations

The XBee®/XBee-PRO® RF Module was designed to mount into a receptacle (socket) and therefore does not require any soldering when mounting it to a board. The XBee Development Kits contain RS-232 and USB interface boards which use two 20-pin receptacles to receive modules.

Figure 1-02. XBee Module Mounting to an RS-232 Interface Board.



The receptacles used on Digi development boards are manufactured by Century Interconnect. Several other manufacturers provide comparable mounting solutions; however, Digi currently uses the following receptacles:

- Through-hole single-row receptacles -
  Samtec P/N: MMS-110-01-L-SV (or equivalent)
- Surface-mount double-row receptacles -
  Century Interconnect P/N: CPRMSL20-D-0-1 (or equivalent)
- Surface-mount single-row receptacles -
  Samtec P/N: SMM-110-02-SM-S

Digi also recommends printing an outline of the module on the board to indicate the orientation the module should be mounted.

Pin Signals

Figure 1-03. XBee®/XBee-PRO® RF Module Pin Numbers

(top sides shown - shields on bottom)

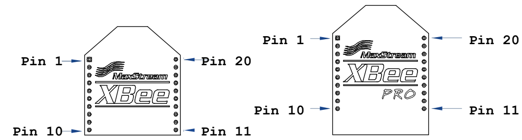


Table 1-02. Pin Assignments for the XBee and XBee-PRO Modules
(Low-asserted signals are distinguished with a horizontal line above signal name.)

Pin #	Name	Direction	Description
1	VCC	-	Power supply
2	DOUT	Output	UART Data Out
3	DIN / $\overline{\text{CONFIG}}$	Input	UART Data In
4	DO8*	Output	Digital Output 8
5	$\overline{\text{RESET}}$	Input	Module Reset (reset pulse must be at least 200 ns)
6	PWM0 / RSSI	Output	PWM Output 0 / RX Signal Strength Indicator
7	PWM1	Output	PWM Output 1
8	[reserved]	-	Do not connect
9	$\overline{\text{DTR}}$ / SLEEP_RQ / DI8	Input	Pin Sleep Control Line or Digital Input 8
10	GND	-	Ground
11	AD4 / DIO4	Either	Analog Input 4 or Digital I/O 4
12	$\overline{\text{CTS}}$ / DIO7	Either	Clear-to-Send Flow Control or Digital I/O 7
13	ON / $\overline{\text{SLEEP}}$	Output	Module Status Indicator
14	VREF	Input	Voltage Reference for A/D Inputs
15	Associate / AD5 / DIO5	Either	Associated Indicator, Analog Input 5 or Digital I/O 5
16	$\overline{\text{RTS}}$ / AD6 / DIO6	Either	Request-to-Send Flow Control, Analog Input 6 or Digital I/O 6
17	AD3 / DIO3	Either	Analog Input 3 or Digital I/O 3
18	AD2 / DIO2	Either	Analog Input 2 or Digital I/O 2
19	AD1 / DIO1	Either	Analog Input 1 or Digital I/O 1
20	AD0 / DIO0	Either	Analog Input 0 or Digital I/O 0

* Function is not supported at the time of this release

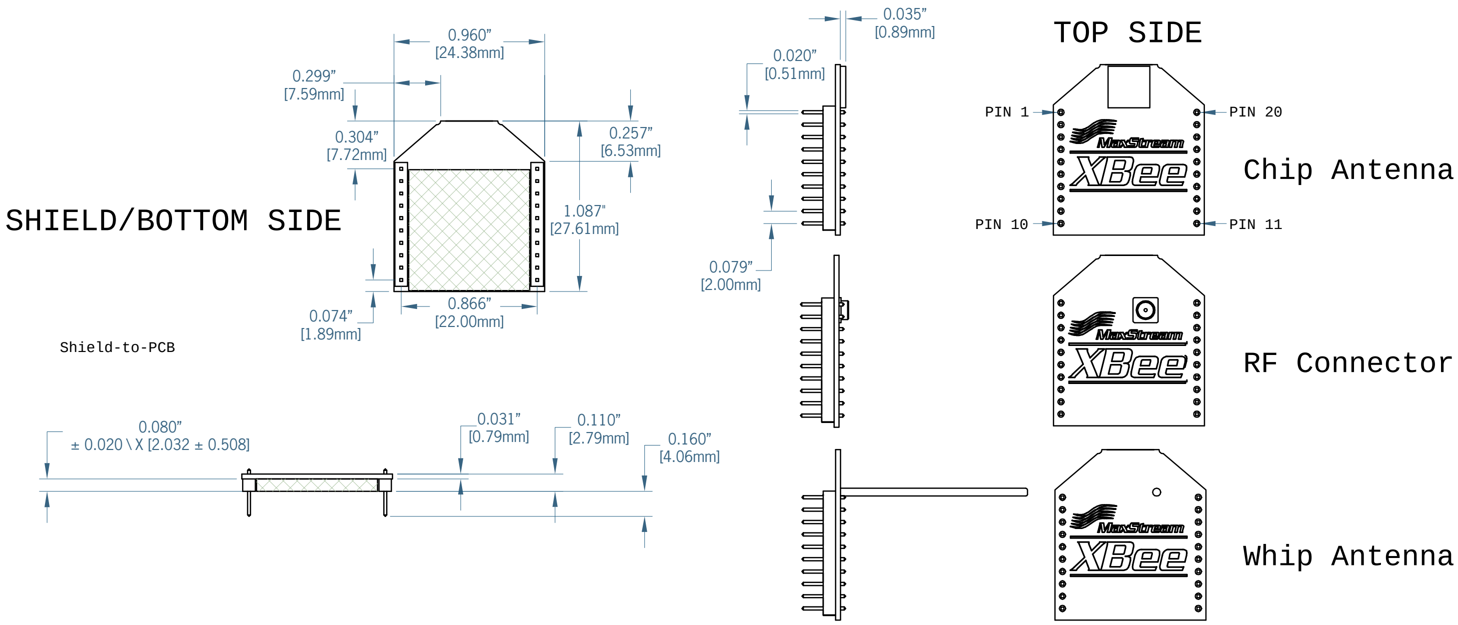
Design Notes:

- Minimum connections: VCC, GND, DOUT & DIN
- Minimum connections for updating firmware: VCC, GND, DIN, DOUT, RTS & DTR
- Signal Direction is specified with respect to the module
- Module includes a 50k Ω pull-up resistor attached to $\overline{\text{RESET}}$
- Several of the input pull-ups can be configured using the PR command
- Unused pins should be left disconnected

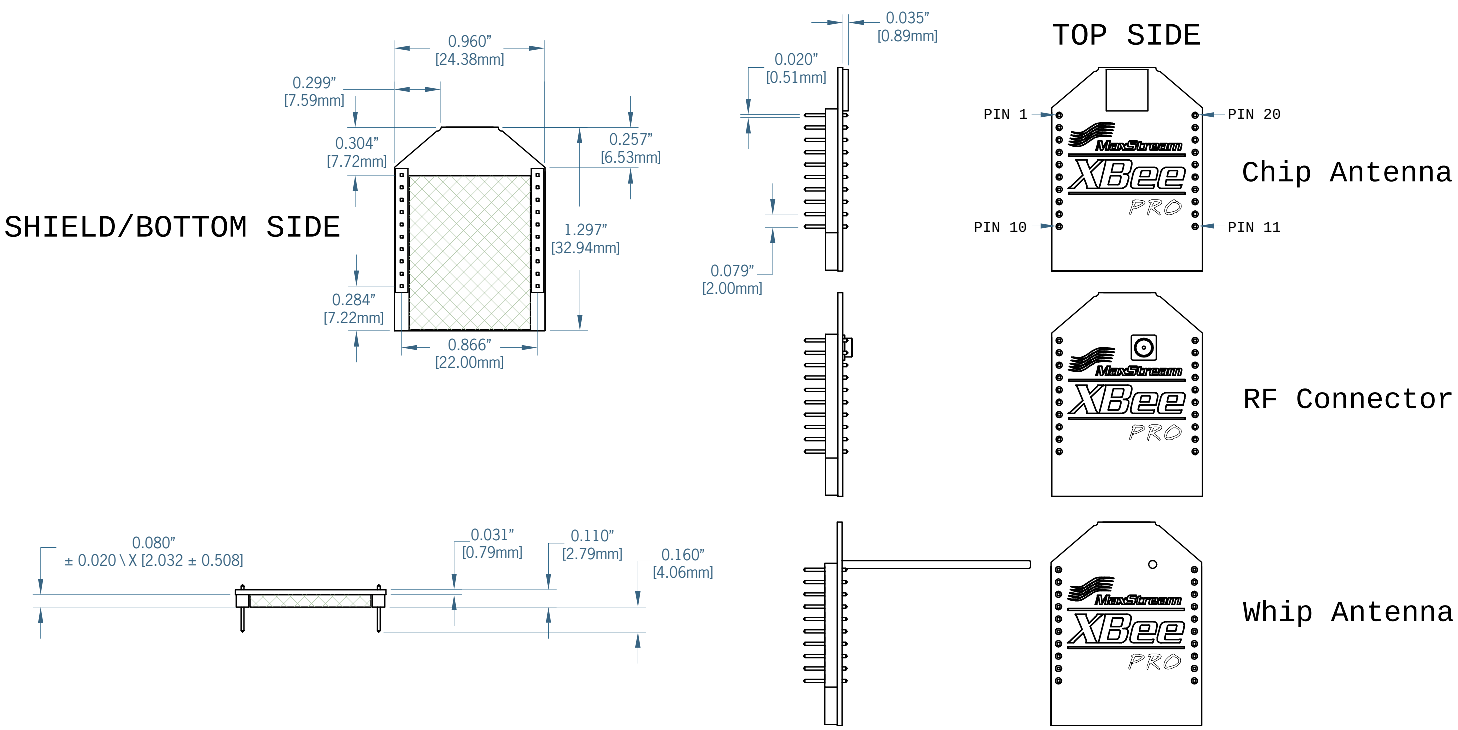
XBee Mechanical Drawings

XBee and XBee-PRO OEM RF Modules are pin-for-pin compatible with each other.

XBee OEM RF Module



XBee-PRO OEM RF Module



M100427 [2006.06.28]

MaxStream®
www.maxstream.net

Phone. (866) 765-9885 Toll-free in U.S. & Canada
(801) 765-9885 Worldwide
Live Chat. www.maxstream.net
E-mail. rf-xperts@maxstream.net

Electrical Characteristics

Table 1-03. DC Characteristics (VCC = 2.8 - 3.4 VDC)

Symbol	Characteristic	Condition	Min	Typical		Max	Unit
V_{IL}	Input Low Voltage	All Digital Inputs	-	-		0.35 * VCC	V
V_{IH}	Input High Voltage	All Digital Inputs	0.7 * VCC	-		-	V
V_{OL}	Output Low Voltage	I_{OL} = 2 mA, VCC >= 2.7 V	-	-		0.5	V
V_{OH}	Output High Voltage	I_{OH} = -2 mA, VCC >= 2.7 V	VCC - 0.5	-		-	V
II_{IN}	Input Leakage Current	V_{IN} = VCC or GND, all inputs, per pin	-	0.025		1	µA
II_{OZ}	High Impedance Leakage Current	V_{IN} = VCC or GND, all I/O High-Z, per pin	-	0.025		1	µA
TX	Transmit Current	VCC = 3.3 V	-	45 (XBee)	215, 140 (PRO, Int)	-	mA
RX	Receive Current	VCC = 3.3 V	-	50 (XBee)	55 (PRO)	-	mA
PWR-DWN	Power-down Current	SM parameter = 1	-	< 10		-	µA

Table 1-04. ADC Characteristics (Operating)

Symbol	Characteristic	Condition	Min	Typical	Max	Unit
V_{REFH}	VREF - Analog-to-Digital converter reference range		2.08	-	V_{DDAD}*	V
I_{REF}	VREF - Reference Supply Current	Enabled	-	200	-	µA
		Disabled or Sleep Mode	-	< 0.01	0.02	µA
V_{INDC}	Analog Input Voltage[1]		V_{SSAD} - 0.3	-	V_{DDAD} + 0.3	V

1. Maximum electrical operating range, not valid conversion range.

* V_{DDAD} is connected to VCC.

Table 1-05. ADC Timing/Performance Characteristics[1]

Symbol	Characteristic	Condition	Min	Typical	Max	Unit
R_{AS}	Source Impedance at Input[2]		-	-	10	kΩ
V_{AIN}	Analog Input Voltage[3]		V_{REFL}		V_{REFH}	V
RES	Ideal Resolution (1 LSB)[4]	2.08V ≤ V_{DDAD} ≤ 3.6V	2.031	-	3.516	mV
DNL	Differential Non-linearity[5]		-	±0.5	±1.0	LSB
INL	Integral Non-linearity[6]		-	±0.5	±1.0	LSB
E_{ZS}	Zero-scale Error[7]		-	±0.4	±1.0	LSB
F_{FS}	Full-scale Error[8]		-	±0.4	±1.0	LSB
E_{IL}	Input Leakage Error[9]		-	±0.05	±5.0	LSB
E_{TU}	Total Unadjusted Error[10]		-	±1.1	±2.5	LSB

1. All ACCURACY numbers are based on processor and system being in WAIT state (very little activity and no IO switching) and that adequate low-pass filtering is present on analog input pins (filter with 0.01 µF to 0.1 µF capacitor between analog input and VREFL). Failure to observe these guidelines may result in system or microcontroller noise causing accuracy errors which will vary based on board layout and the type and magnitude of the activity.
Data transmission and reception during data conversion may cause some degradation of these specifications, depending on the number and timing of packets. It is advisable to test the ADCs in your installation if best accuracy is required.
2. R_{AS} is the real portion of the impedance of the network driving the analog input pin. Values greater than this amount may not fully charge the input circuitry of the ATD resulting in accuracy error.
3. Analog input must be between V_{REFL} and V_{REFH} for valid conversion. Values greater than V_{REFH} will convert to $3FF.
4. The resolution is the ideal step size or 1LSB = $(V_{REFH}–V_{REFL})/1024$
5. Differential non-linearity is the difference between the current code width and the ideal code width (1LSB). The current code width is the difference in the transition voltages to and from the current code.
6. Integral non-linearity is the difference between the transition voltage to the current code and the adjusted ideal transition voltage for the current code. The adjusted ideal transition voltage is (Current Code–1/2)*(1/((V_{REFH}+E_{FS})–(V_{REFL}+E_{ZS}))).
7. Zero-scale error is the difference between the transition to the first valid code and the ideal transition to that code. The Ideal transition voltage to a given code is (Code–1/2)*(1/(V_{REFH}–V_{REFL})).
8. Full-scale error is the difference between the transition to the last valid code and the ideal transition to that code. The ideal transition voltage to a given code is (Code–1/2)*(1/(V_{REFH}–V_{REFL})).
9. Input leakage error is error due to input leakage across the real portion of the impedance of the network driving the analog pin. Reducing the impedance of the network reduces this error.

Part VI.

Code

Galileo Code

```
#include <Servo.h> // Servo Library
Servo esc;
int low = 13;
int med = 12;
int hi = 11;     // Initialize pins
int val = 0;
int ledPin = 7;

void setup()
{
 esc.attach(9);
 delay(1);
 esc.write(40);                    // Arm ESC

 pinMode(low, INPUT);
 pinMode(med, INPUT);
 pinMode(hi, INPUT);
 pinMode(ledPin, OUTPUT);
}

void loop()
{
 if (digitalRead(low) == LOW)
 {
  digitalWrite(ledPin, HIGH);
  esc.write(75);          // Low Speed, 8mph
 }
 else if (digitalRead(med) == LOW)
 {
  digitalWrite(ledPin, HIGH);
```

```
  esc.write(90);          // Medium Speed, 12mph
 }
 else if (digitalRead(hi) == LOW)
 {
  digitalWrite(ledPin, HIGH);
  esc.write(115);         // High Speed, 15mph
 }
 else
 {
  digitalWrite(ledPin, LOW);
  esc.write(50);          // Default, no speed
 }
}
```

Part VII.

Results

Figure 12. Brushless DC Motor

Figure 13. Motor controller

Figure 14. Microcontroller Battery

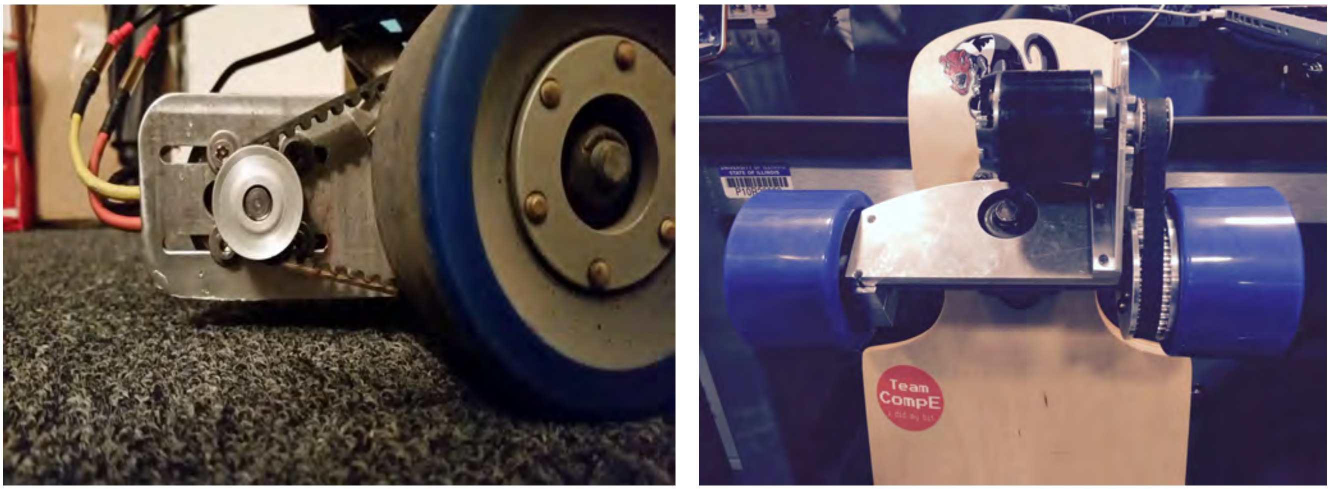


Figure 15. Motor Mounter

Figure 16. Motor Battery

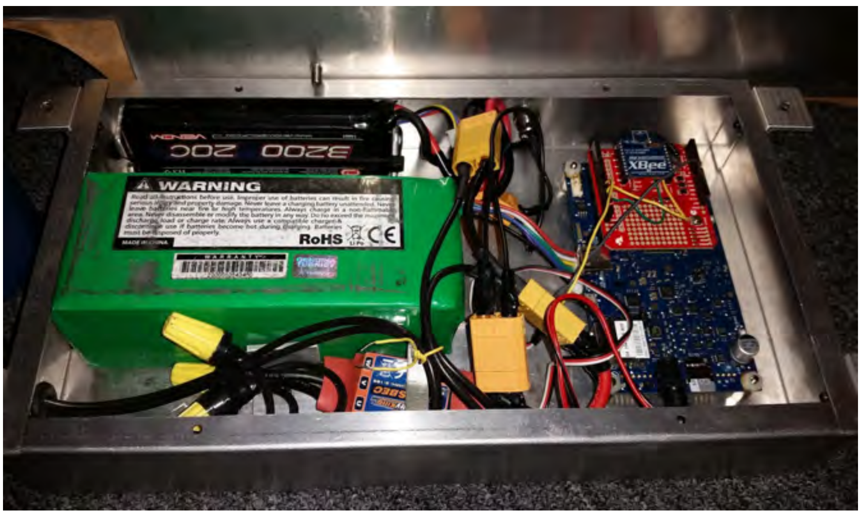


Figure 17. Protecting Box

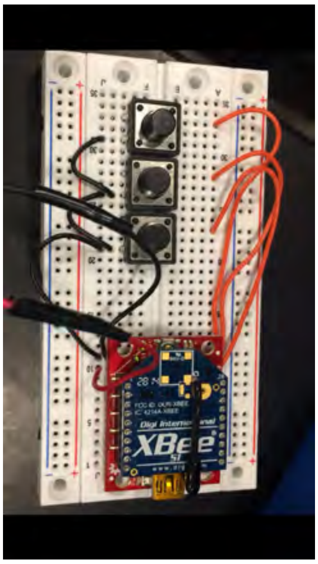


Figure 18. Remote Controller

Figure 19. Final Result

Part VIII.

Schematics

REVISION HISTORY				
ZONE	REV	DESCRIPTION	DATE	APPROVED

GALILEO

INTEL QUARK X1000

FAB D

PB: G87173-204

PBA:G87171-400

LB1

EMPTY

WEEE_LABEL_9X5MM

WEEE

LB6V1

LABEL

1500X500_TARGET

SERIAL NUMBER

LB3

LABEL

1375X250_TARGET

MAC ADDRESS LABEL

DRAWN BY	DATE	INTEL CORPORATION 2111 NE 25TH AVENUE HILLSBORO OR 97124
APPROVED BY	DATE	

TITLE	DOCUMENT NUMBER	REV
GALILEO	G87171	1.0
	SHEET 1 OF 27	

TABLE OF CONTENTS

INTEL CORPORATION
2111 NE 25TH AVENUE
HILLSBORO OR 97124

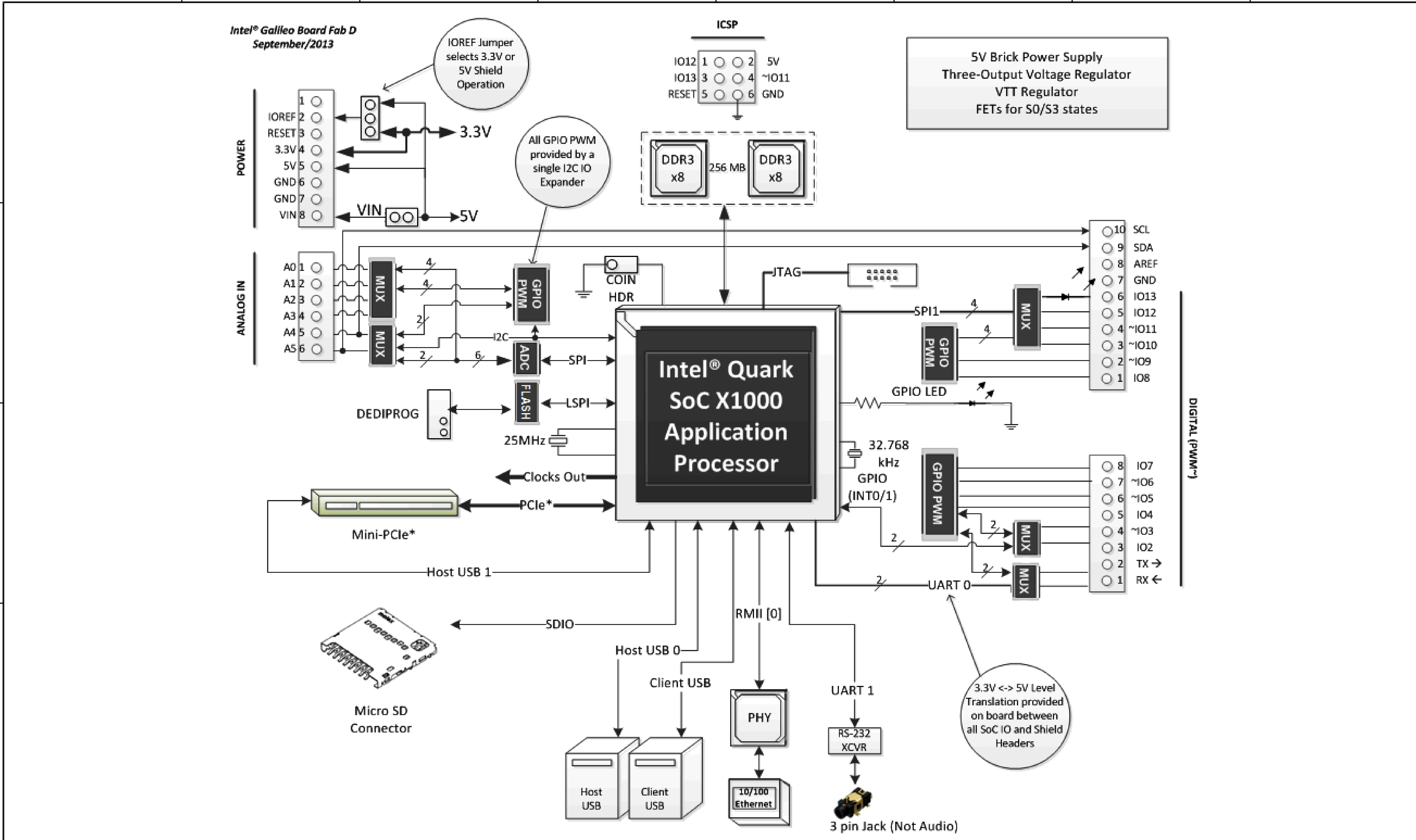
TITLE: GALILEO
TABLE OF CONTENTS

DOCUMENT NUMBER: G87171

REV: 1.0

ENJOY!

INTEL CORPORATION 2111 NE 25TH AVENUE HILLSBORO OR 97124	DOCUMENT NUMBER: G87171
TITLE: GALILEO DISCLAIMER	REV: 1.0 SHEET 3 OF 27



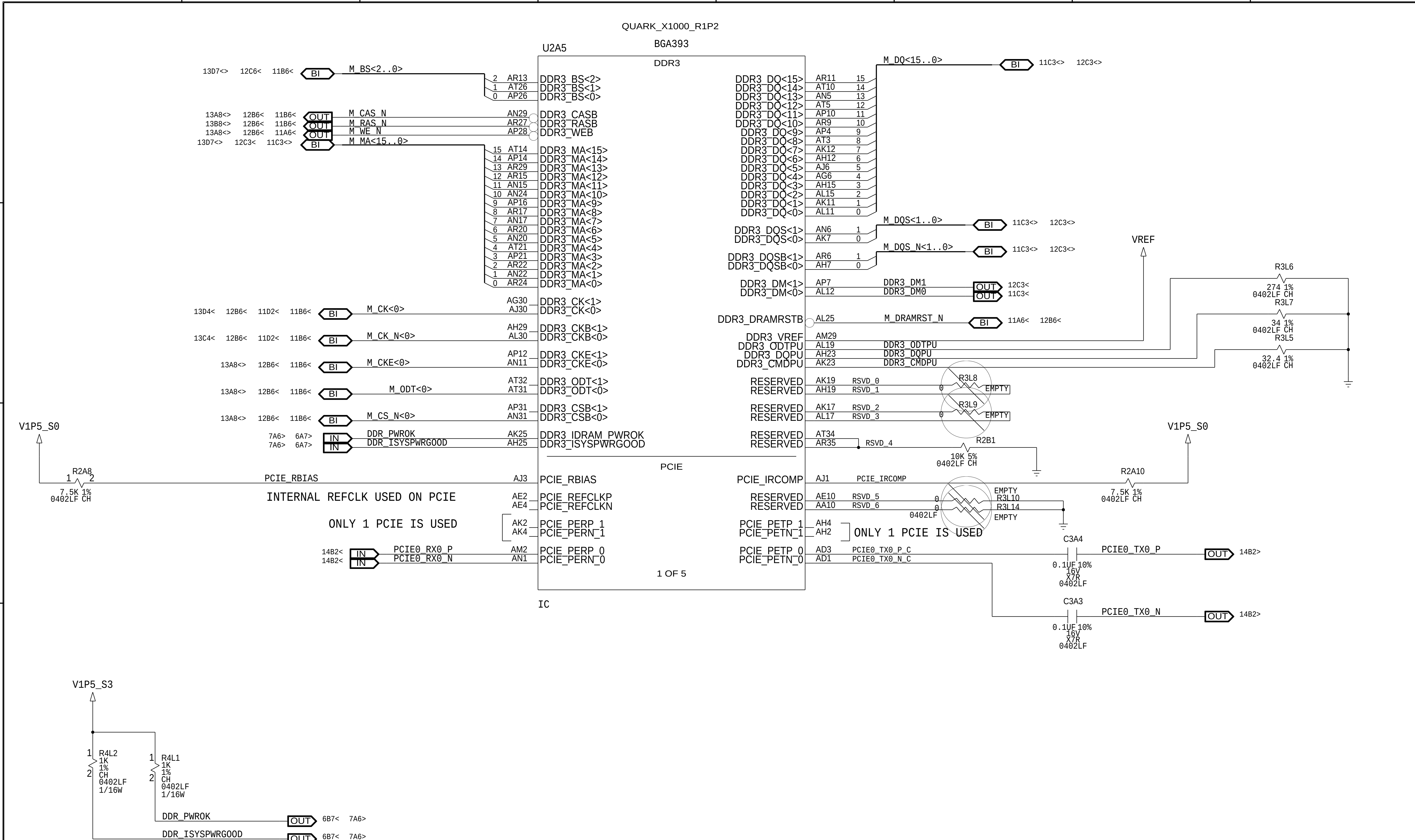
INTEL CORPORATION
2111 NE 25TH AVENUE
HILLSBORO OR 97124

TITLE: GALILEO
SYSTEM BLOCK DIAGRAM

DOCUMENT NUMBER: G87171

REV: 1.0

SHEET 4 OF 27

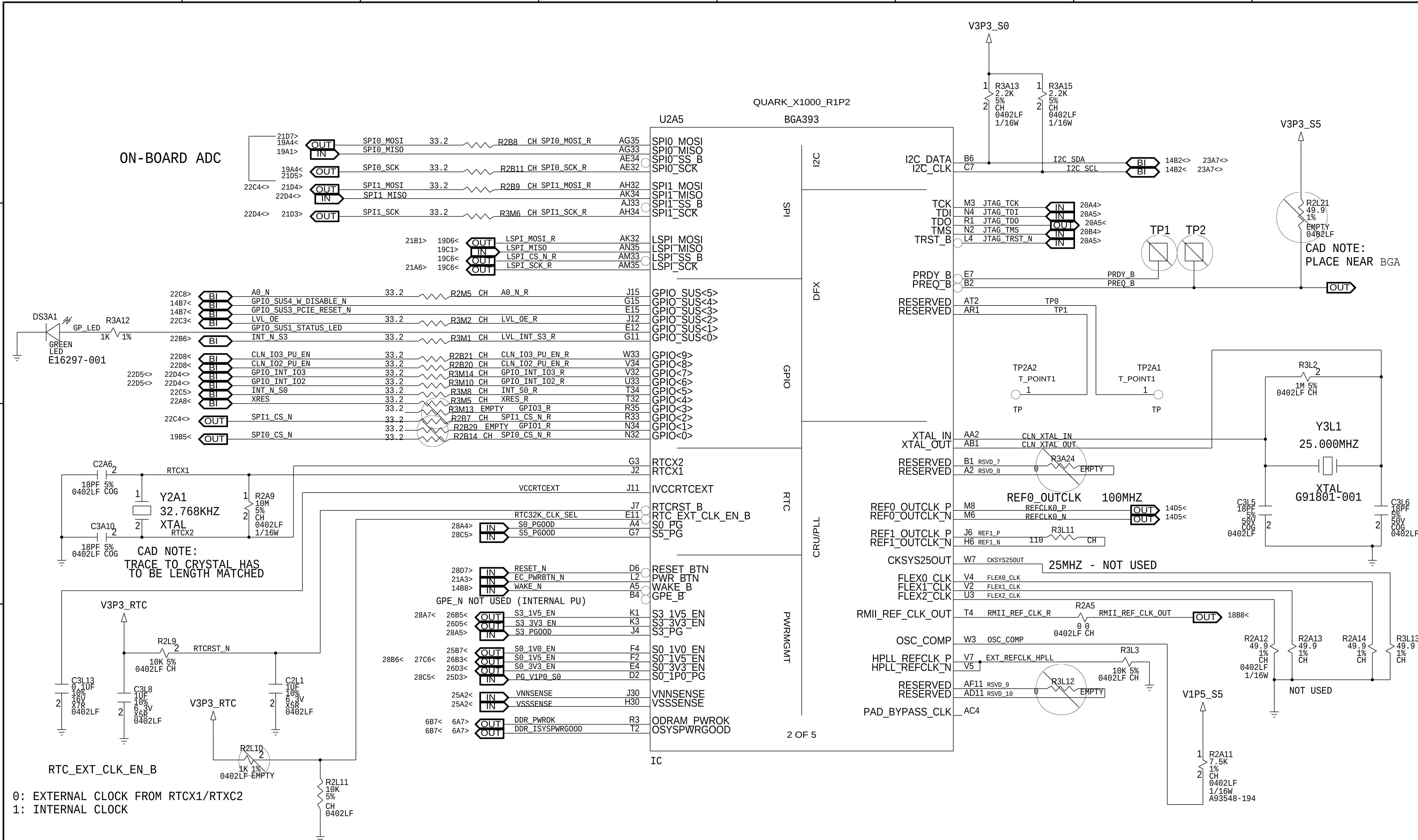


INTEL CORPORATION
2111 NE 25TH AVENUE
HILLSBORO OR 97124

TITLE: GALILEO QUARK DDR3 & PCIE

DOCUMENT NUMBER: G87171

REV: 1.0 | SHEET 5 OF 27



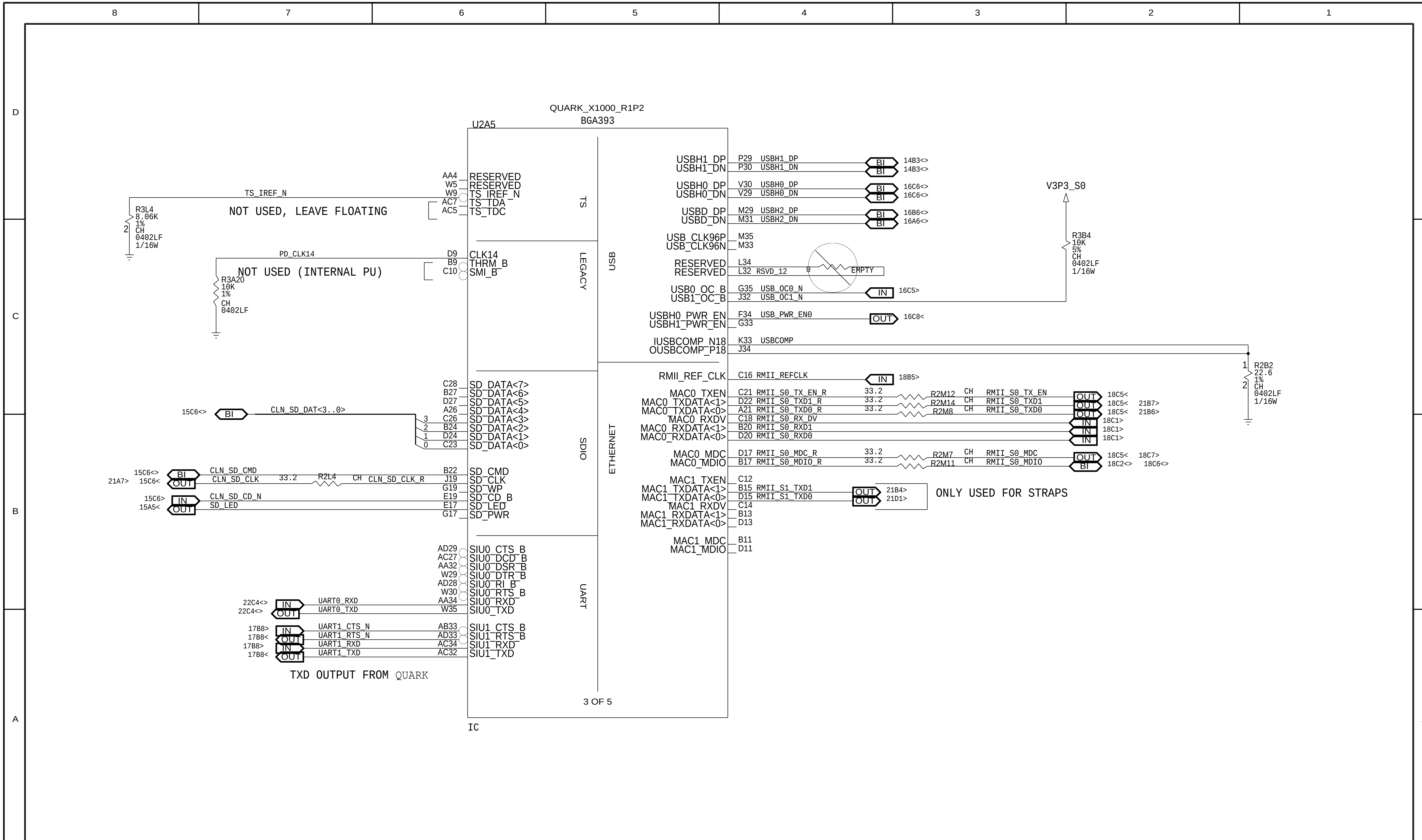
INTEL CORPORATION
2111 NE 25TH AVENUE
HILLSBORO OR 97124

TITLE: GALILEO QUARK GPIO

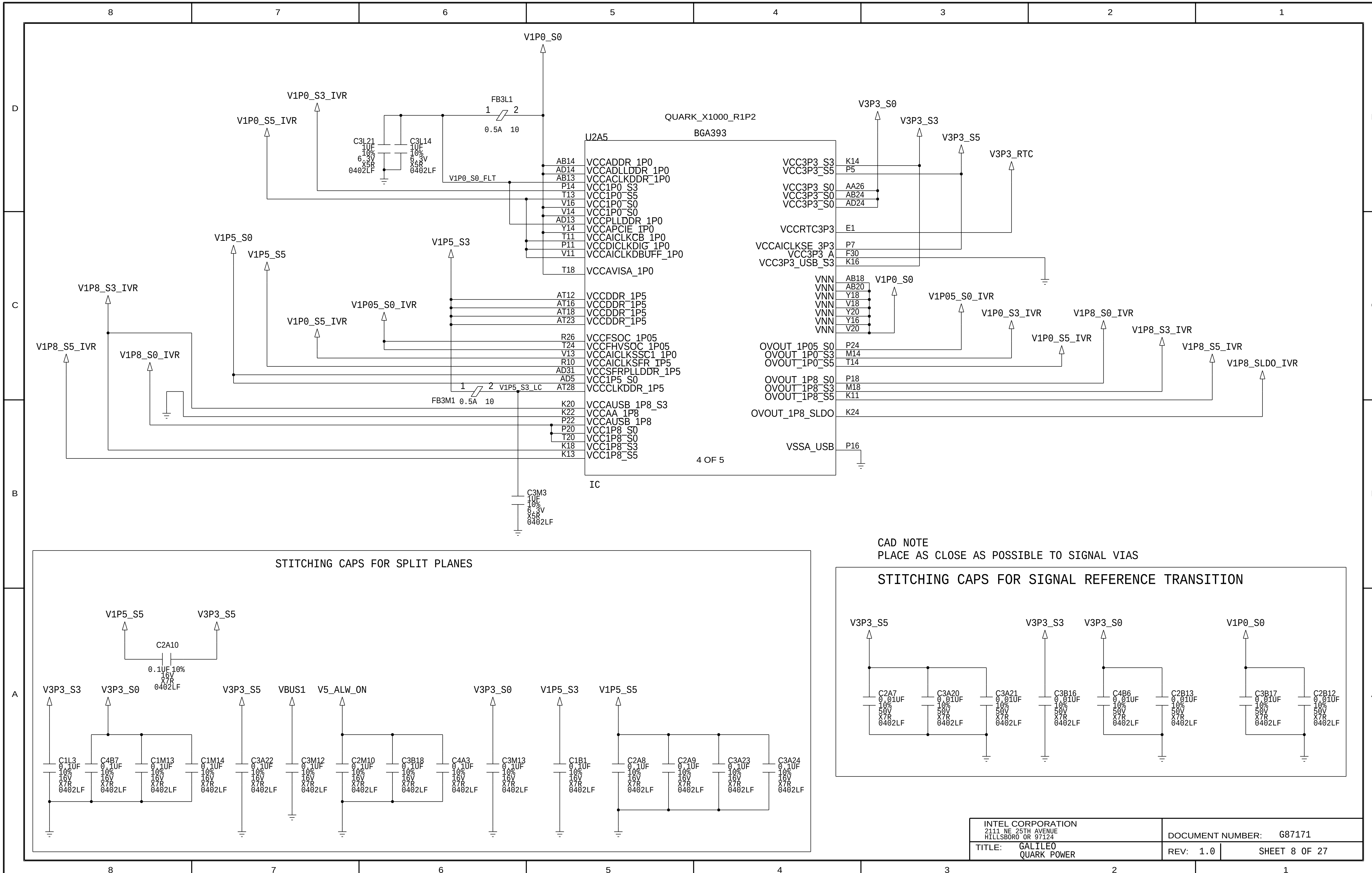
DOCUMENT NUMBER: G87171

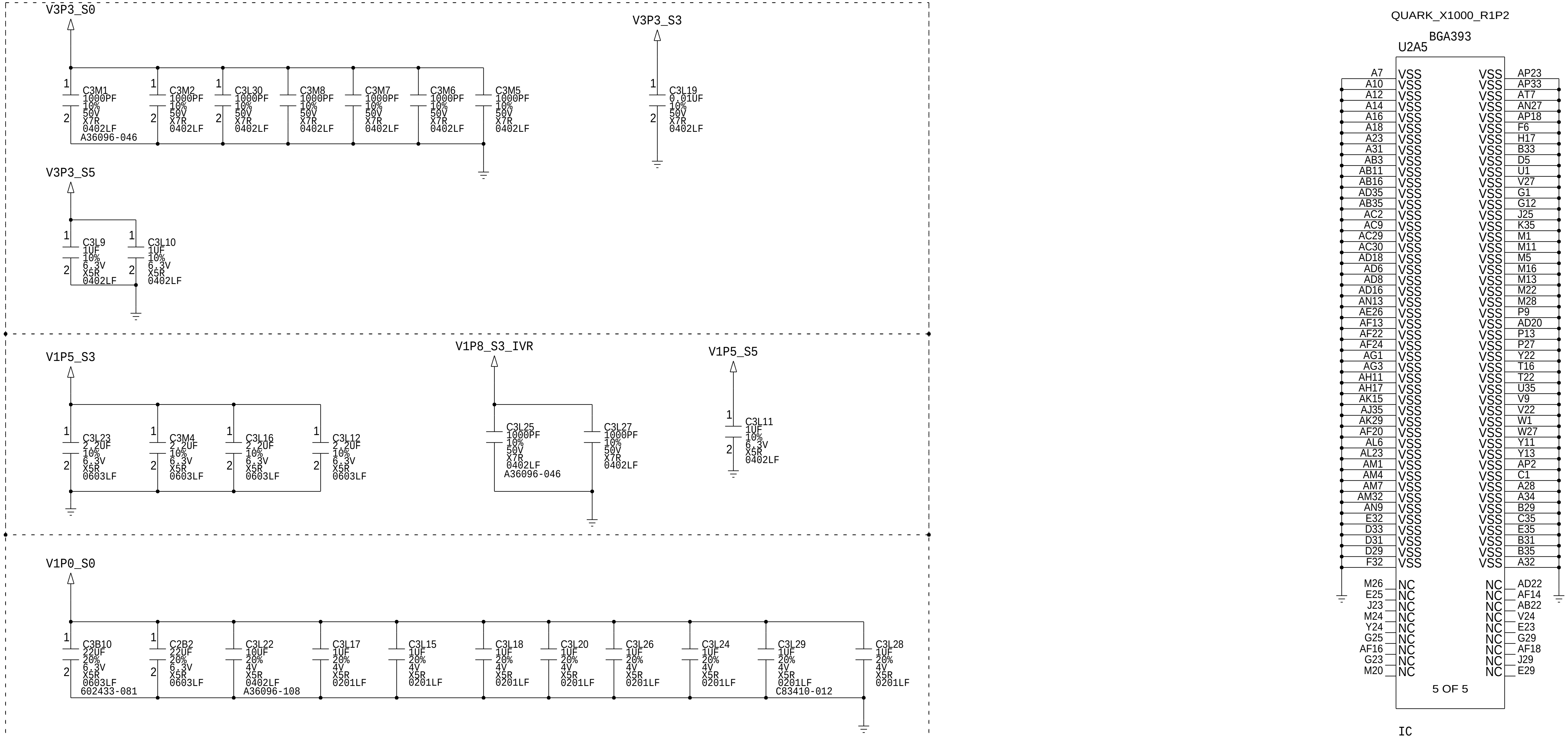
REV: 1.0

SHEET 6 OF 27

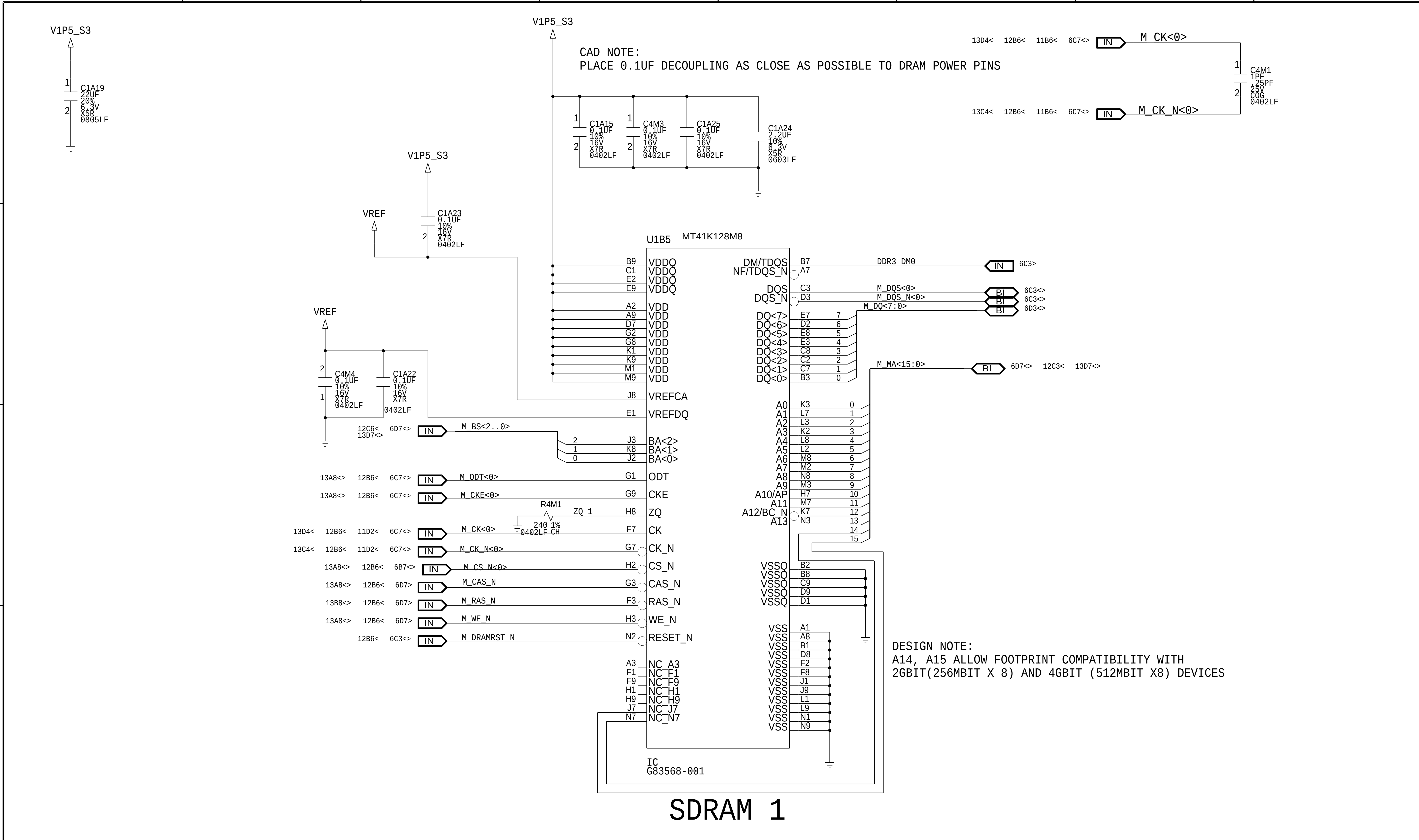


INTEL CORPORATION 2111 NE 25TH AVENUE HILLSBORO OR 97124	DOCUMENT NUMBER: G87171	
TITLE: GALILEO QUARK MISC	REV: 1.0	SHEET 7 OF 27


QUARK_X1000_R1P2
U2A5
BGA393
4 OF 5
IC
FB3L1
0.5A 10
FB3M1
V1P0_S0_FLT
V1P5_S3_LC
C3L21 1UF 10% 6.3V X5R 0402LF
C3L14 1UF 10% 6.3V X5R 0402LF
C3M3 1UF 10% 6.3V X5R 0402LF
VCCADDR_1P0
VCCADLLDDR_1P0
VCCACLKDDR_1P0
VCC1P0_S3
VCC1P0_S5
VCC1P0_S0
VCCPLLDDR_1P0
VCCAPCIE_1P0
VCCAICLKCB_1P0
VCCDICLKDIG_1P0
VCCAICLKDBUFF_1P0
VCCAVISA_1P0
VCCDDR_1P5
VCCFSOC_1P05
VCCFHVSOC_1P05
VCCAICLKSSC1_1P0
VCCAICLKSFR_1P5
VCCSFRPLLDDR_1P5
VCC1P5_S0
VCCCLKDDR_1P5
VCCAUSB_1P8_S3
VCCAA_1P8
VCCAUSB_1P8
VCC1P8_S0
VCC1P8_S3
VCC1P8_S5
VCC3P3_S3
VCC3P3_S5
VCC3P3_S0
VCCRTC3P3
VCCAICLKSE_3P3
VCC3P3_A
VCC3P3_USB_S3
VNN
OVOUT_1P05_S0
OVOUT_1P0_S3
OVOUT_1P0_S5
OVOUT_1P8_S0
OVOUT_1P8_S3
OVOUT_1P8_S5
OVOUT_1P8_SLDO
VSSA_USB
STITCHING CAPS FOR SPLIT PLANES
C2A10 0.1UF 10% 16V X7R 0402LF
CAD NOTE
PLACE AS CLOSE AS POSSIBLE TO SIGNAL VIAS
STITCHING CAPS FOR SIGNAL REFERENCE TRANSITION
INTEL CORPORATION
2111 NE 25TH AVENUE
HILLSBORO OR 97124
TITLE: GALILEO QUARK POWER
DOCUMENT NUMBER: G87171
REV: 1.0
SHEET 8 OF 27



INTEL CORPORATION 2111 NE 25TH AVENUE HILLSBORO OR 97124	DOCUMENT NUMBER: G87171
TITLE: GALILEO QUARK DECOUPLING	REV: 1.0 — SHEET 9 OF 27



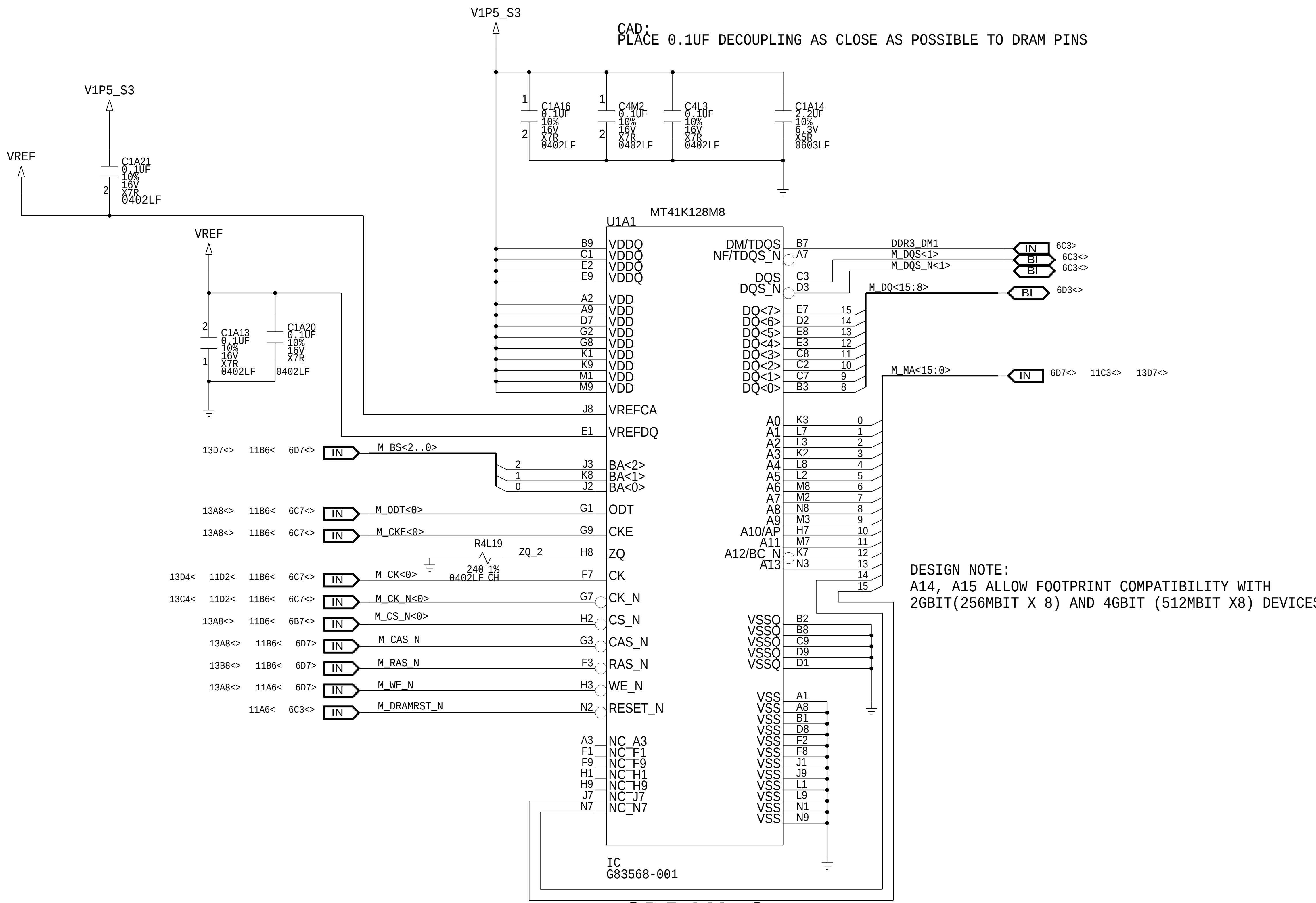
INTEL CORPORATION
2111 NE 25TH AVENUE
HILLSBORO OR 97124

TITLE: GALILEO SDRAM 1

DOCUMENT NUMBER: G87171

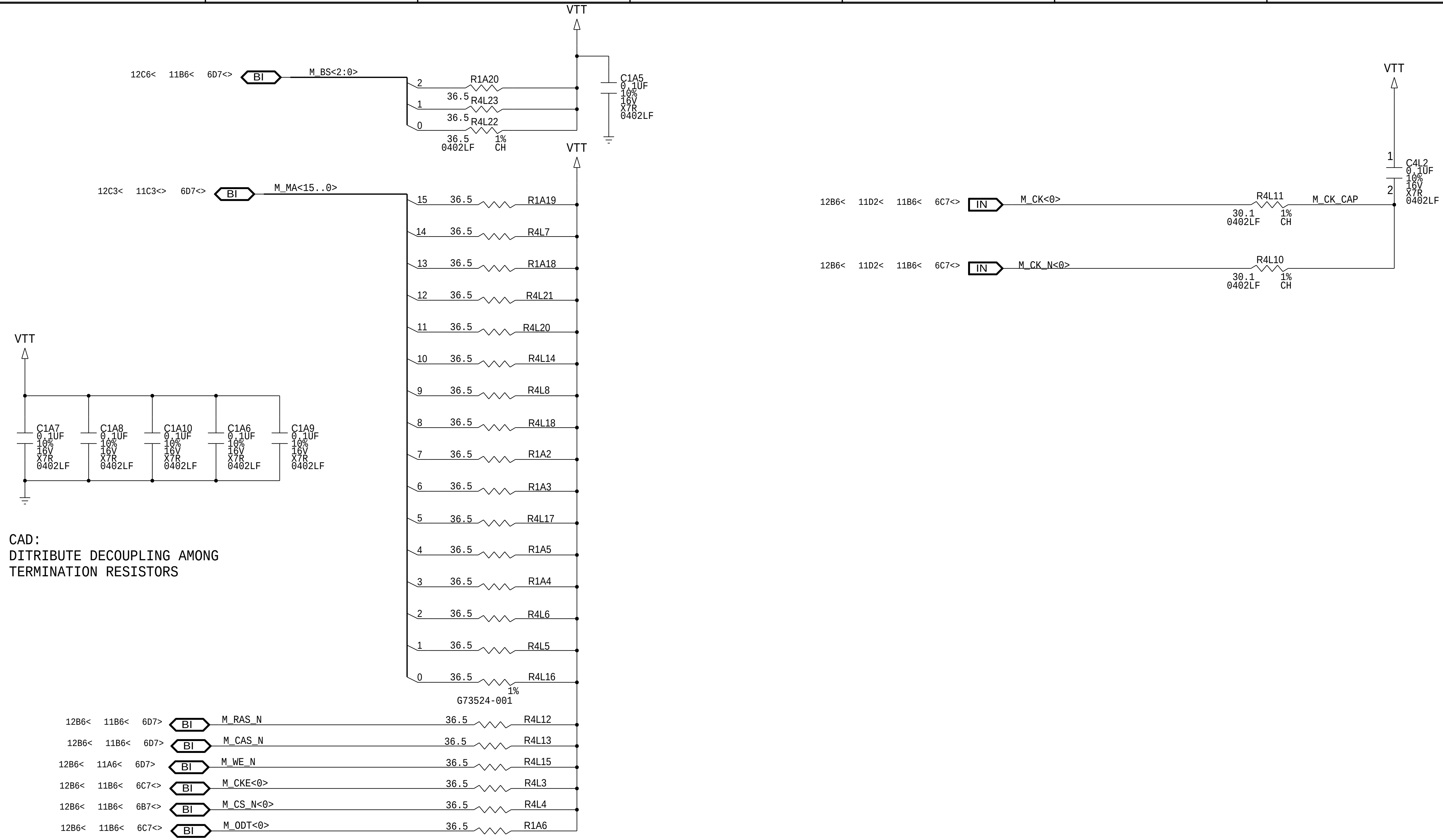
REV: 1.0

SHEET 10 OF 27



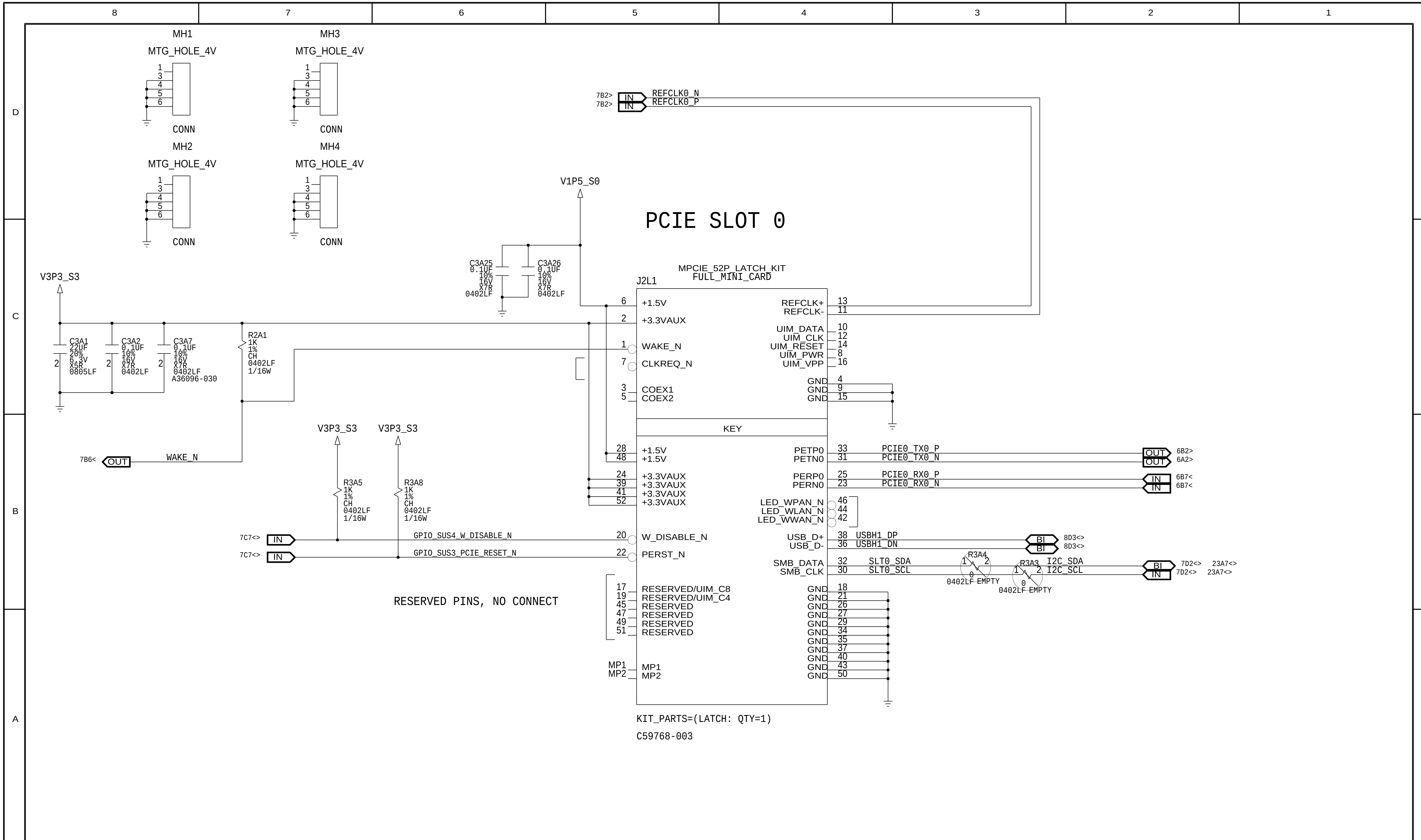
SDRAM 2

INTEL CORPORATION 2111 NE 25TH AVENUE HILLSBORO OR 97124	DOCUMENT NUMBER: G87171
TITLE: GALILEO SDRAM 2	REV: 1.0 — SHEET 11 OF 27



INTEL CORPORATION
2111 NE 25TH AVENUE
HILLSBORO OR 97124

TITLE: GALILEO SDRAM TERMINATION	DOCUMENT NUMBER: G87171
REV: 1.0	SHEET 12 OF 27



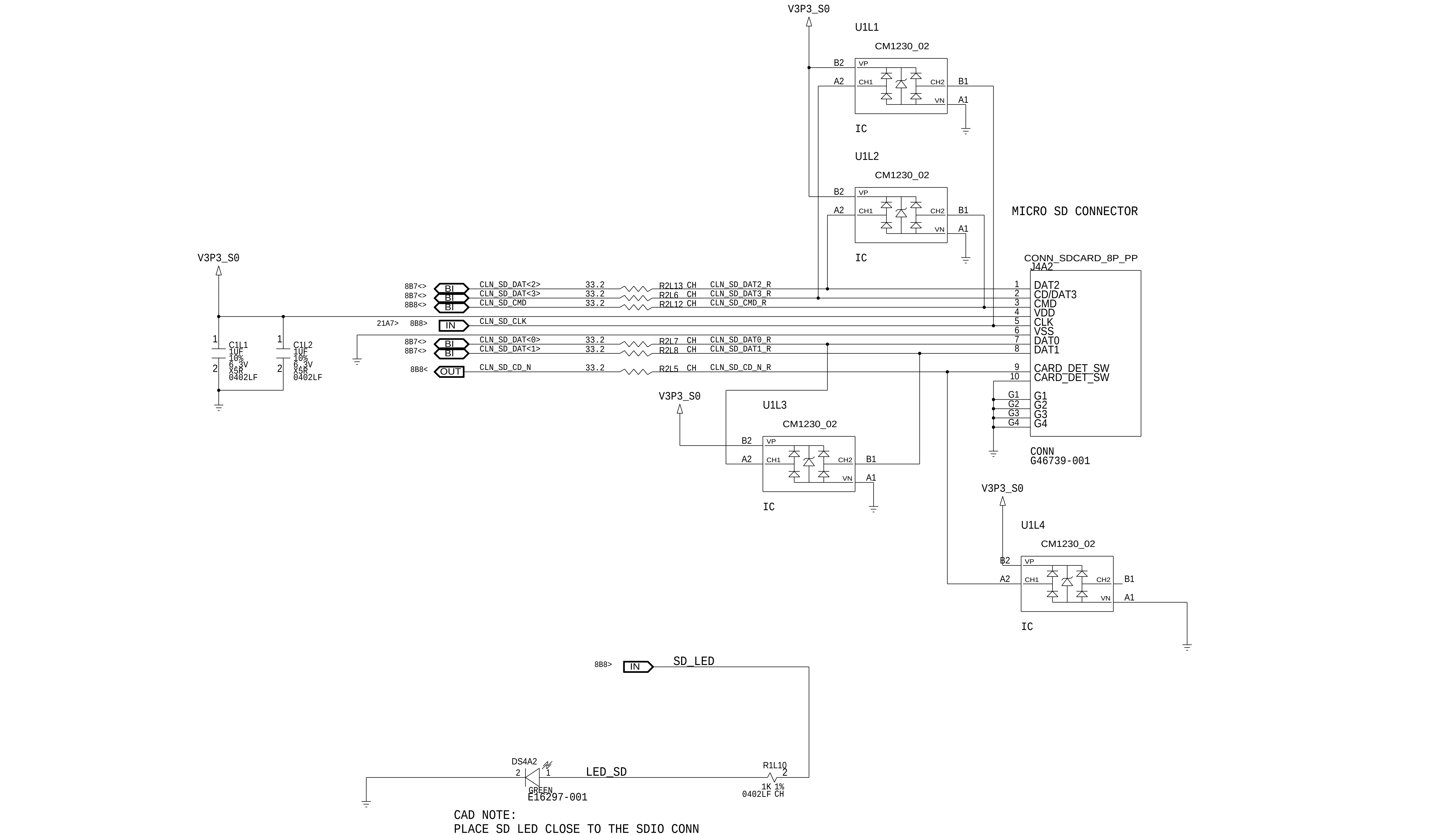
INTEL CORPORATION
2111 NE 25TH AVENUE
HILLSBORO OR 97124

DOCUMENT NUMBER: G87171

TITLE: GALILEO
MINI PCIE CONNECTOR

REV: 1.0

SHEET 13 OF 27

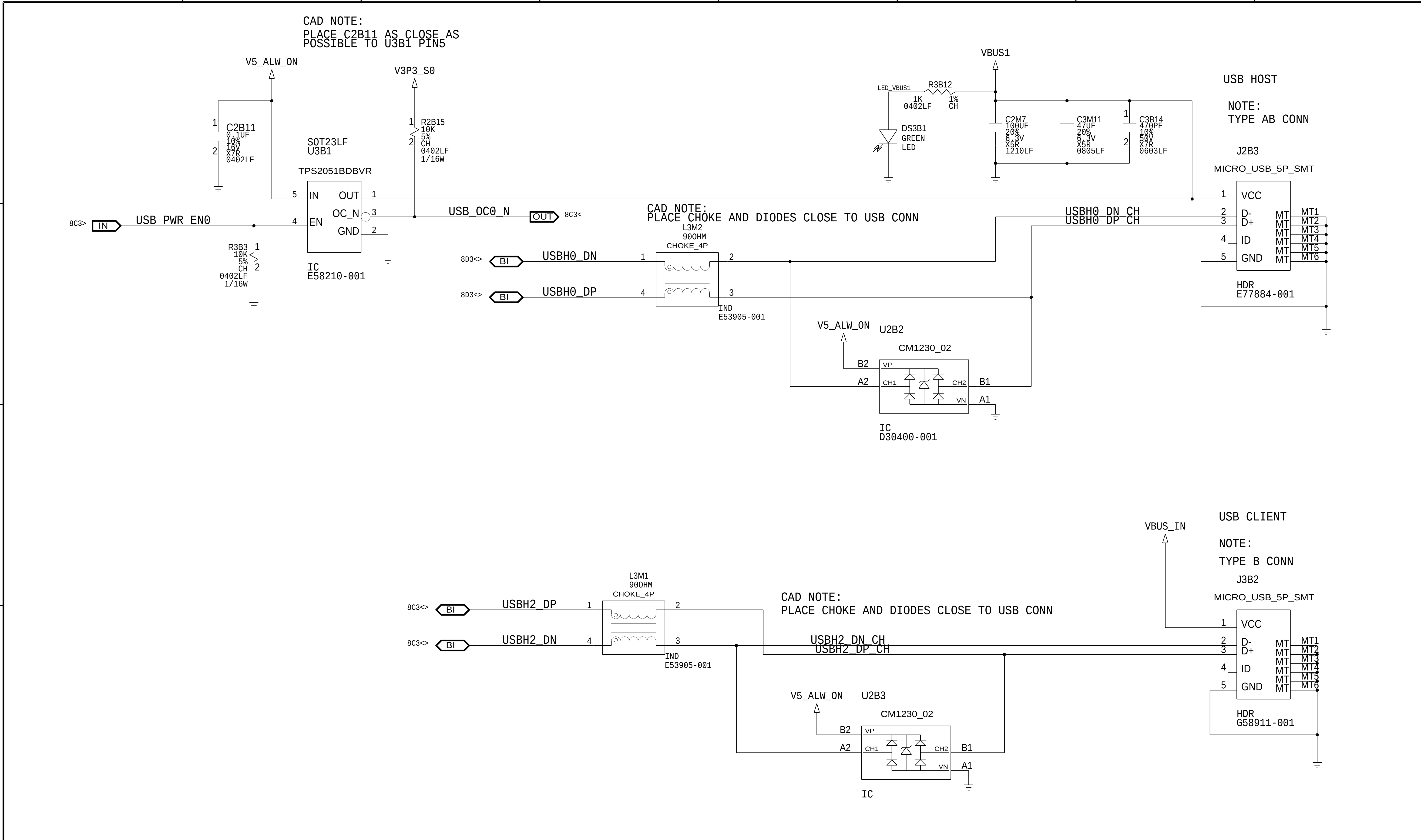


INTEL CORPORATION
2111 NE 25TH AVENUE
HILLSBORO OR 97124

TITLE: GALILEO
MICRO SD CONNECTOR

DOCUMENT NUMBER: G87171

REV: 1.0 | SHEET 14 OF 27



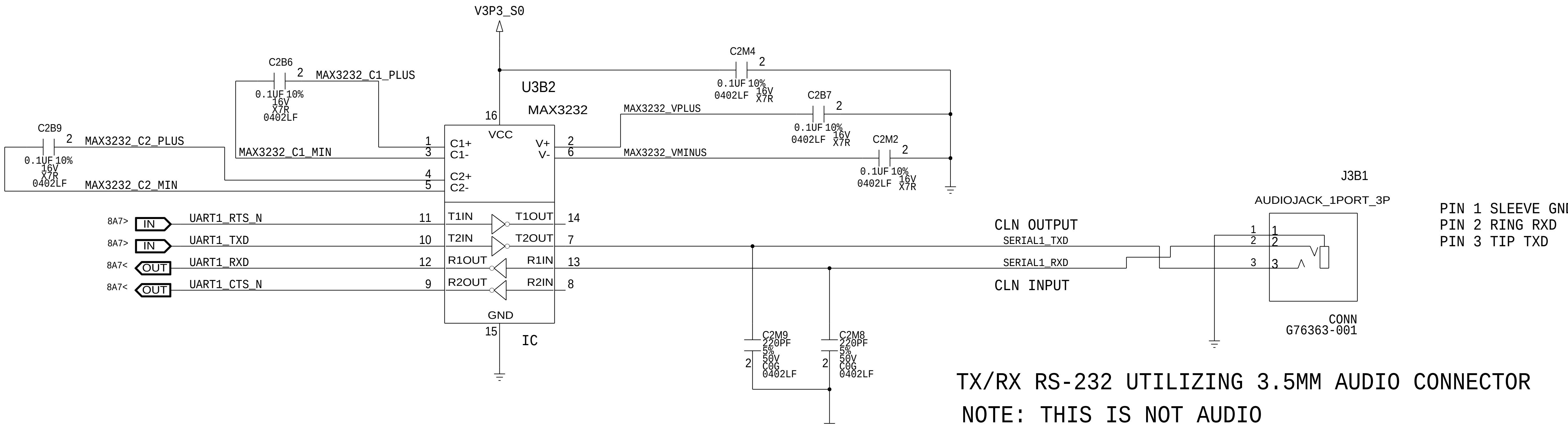
INTEL CORPORATION
2111 NE 25TH AVENUE
HILLSBORO OR 97124

TITLE: GALILEO
USB CONNECTORS

DOCUMENT NUMBER: G87171

REV: 1.0

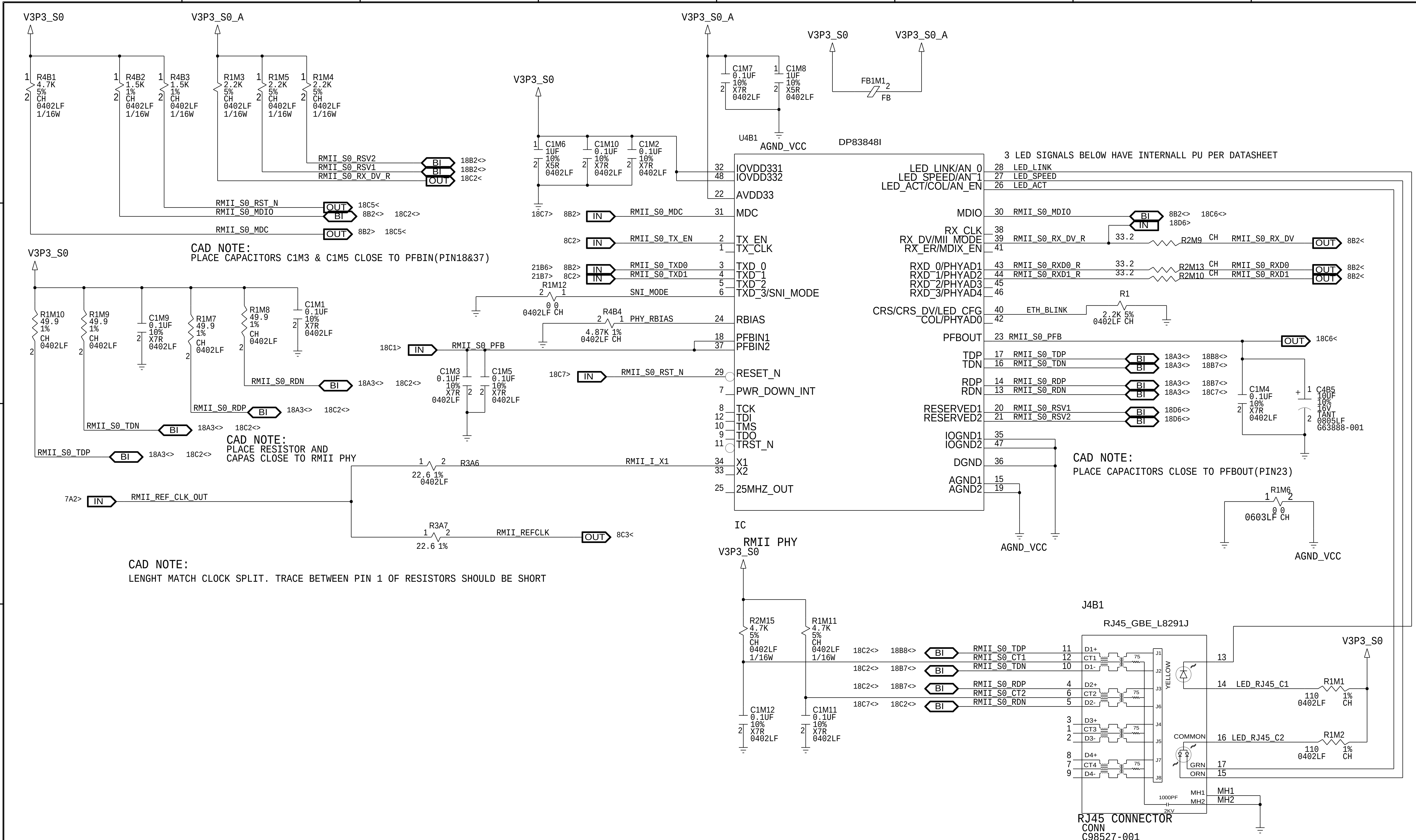
SHEET 15 OF 27



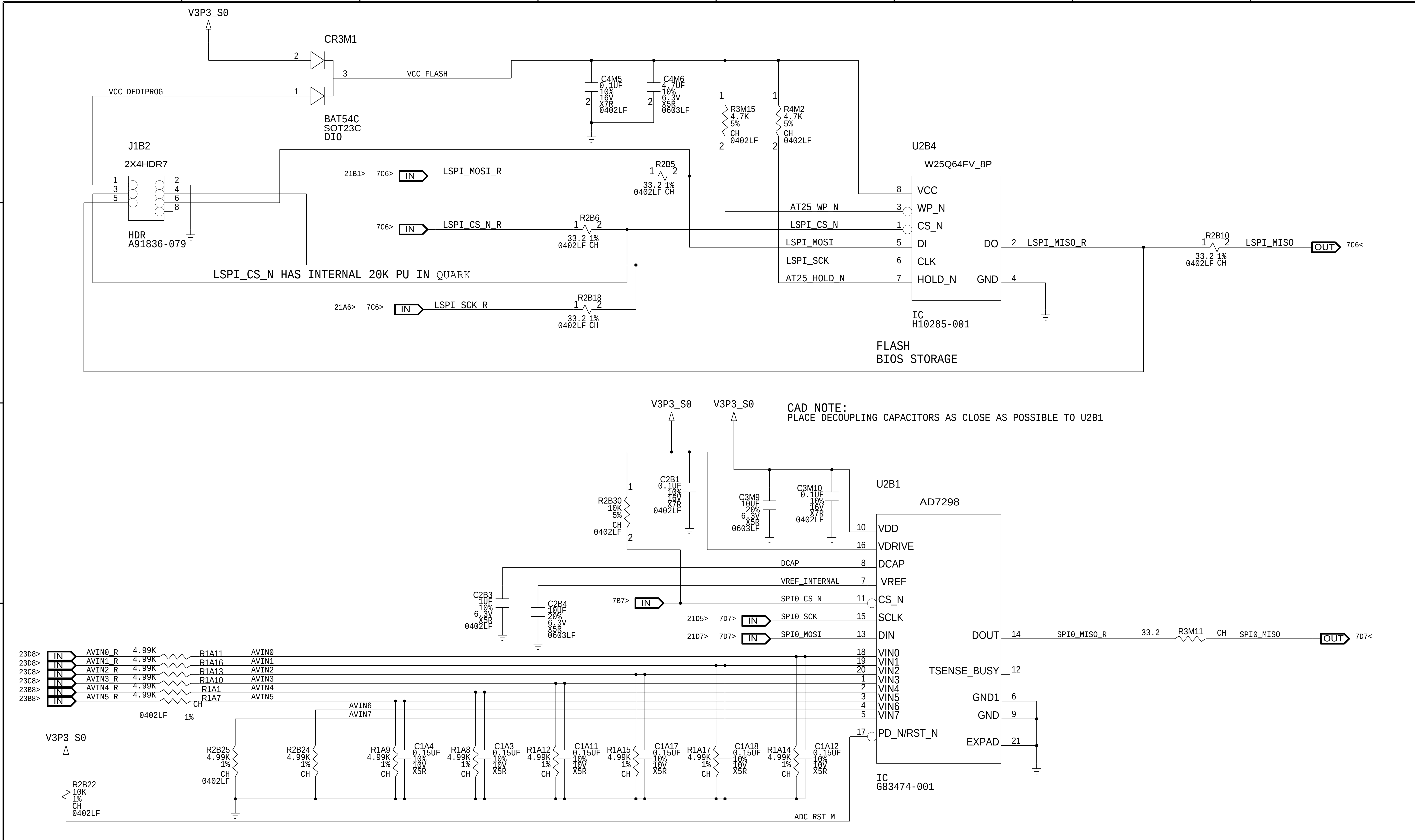
TX/RX RS-232 UTILIZING 3.5MM AUDIO CONNECTOR

NOTE: THIS IS NOT AUDIO

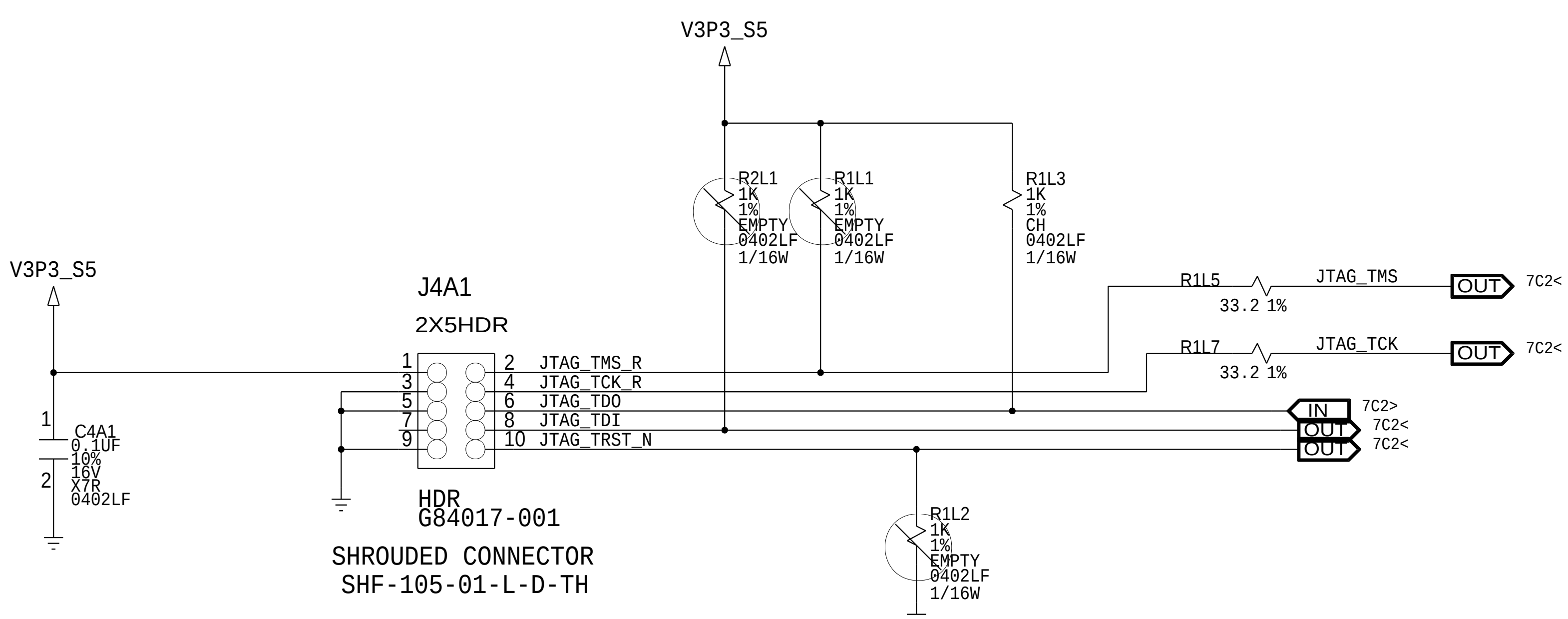
INTEL CORPORATION 2111 NE 25TH AVENUE HILLSBORO OR 97124	DOCUMENT NUMBER: G87171
TITLE: GALILEO UART 1	REV: 1.0 — SHEET 16 OF 27



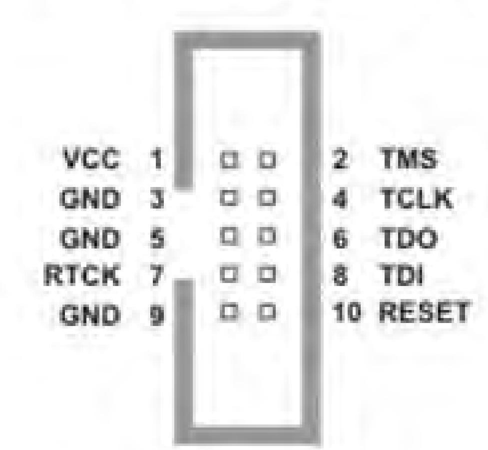
INTEL CORPORATION 2111 NE 25TH AVENUE HILLSBORO OR 97124	DOCUMENT NUMBER: G87171
TITLE: GALILEO LAN	REV: 1.0 SHEET 17 OF 27



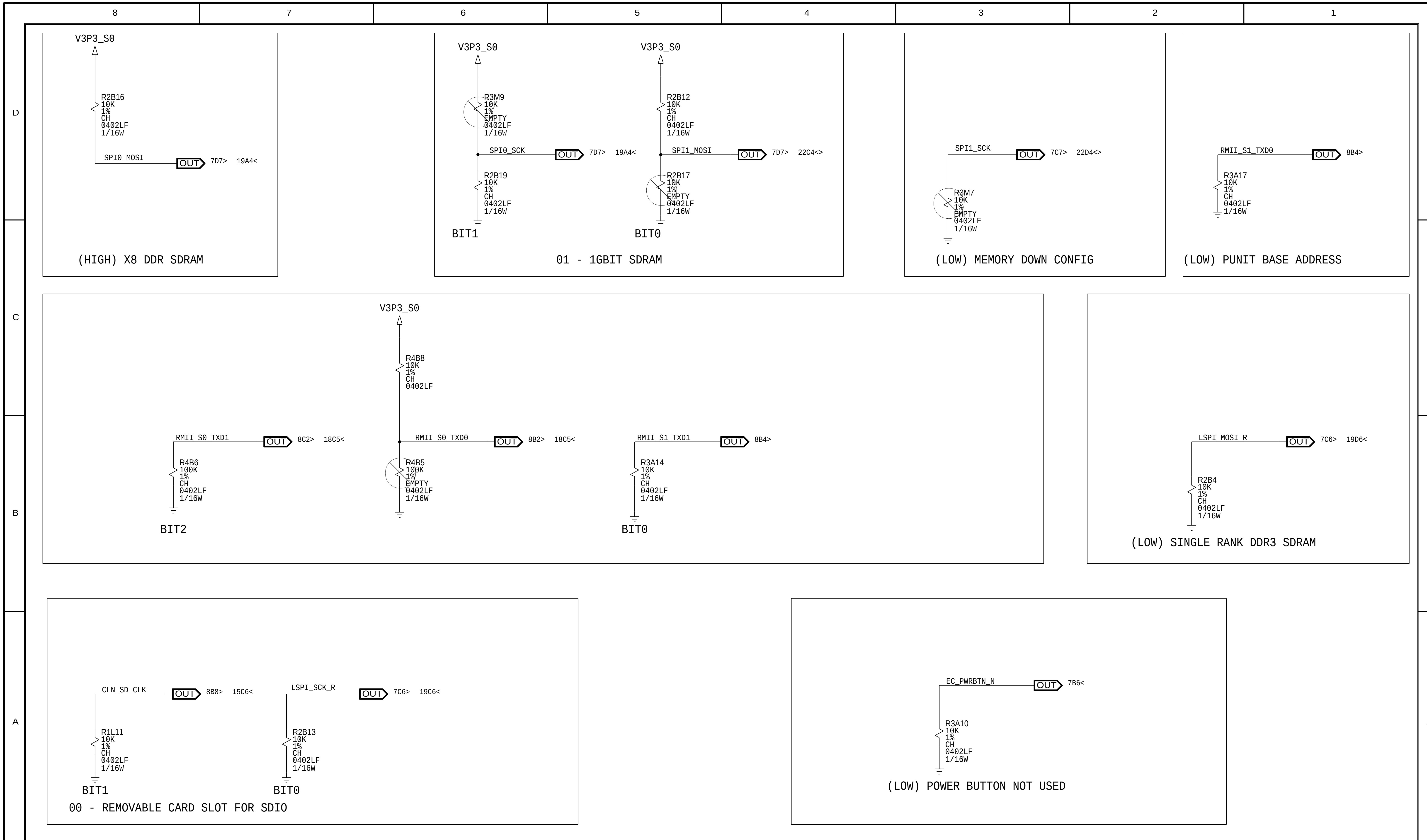
INTEL CORPORATION 2111 NE 25TH AVENUE HILLSBORO OR 97124	DOCUMENT NUMBER: G87171
TITLE: GALILEO SPI: ADC&FLASH	REV: 1.0 SHEET 18 OF 27



MINI-JTAG CONNECTOR



INTEL CORPORATION 2111 NE 25TH AVENUE HILLSBORO OR 97124	DOCUMENT NUMBER: G87171
TITLE: GALILEO I2CPROM & JTAG CONN	REV: 1.0 SHEET 19 OF 27



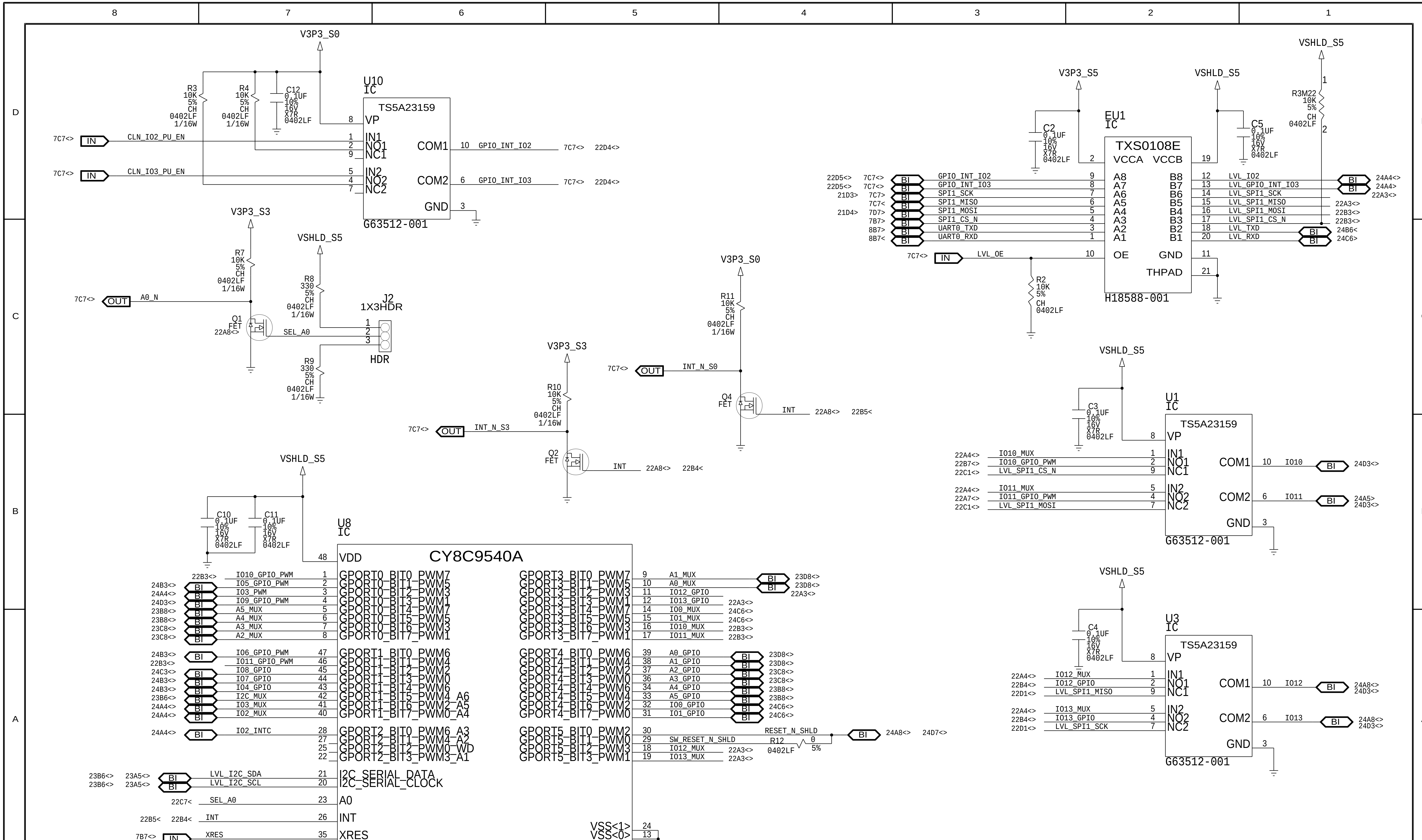
INTEL CORPORATION
2111 NE 25TH AVENUE
HILLSBORO OR 97124

TITLE: GALILEO
QUARK STRAPS

DOCUMENT NUMBER: G87171

REV: 1.0

SHEET 20 OF 27



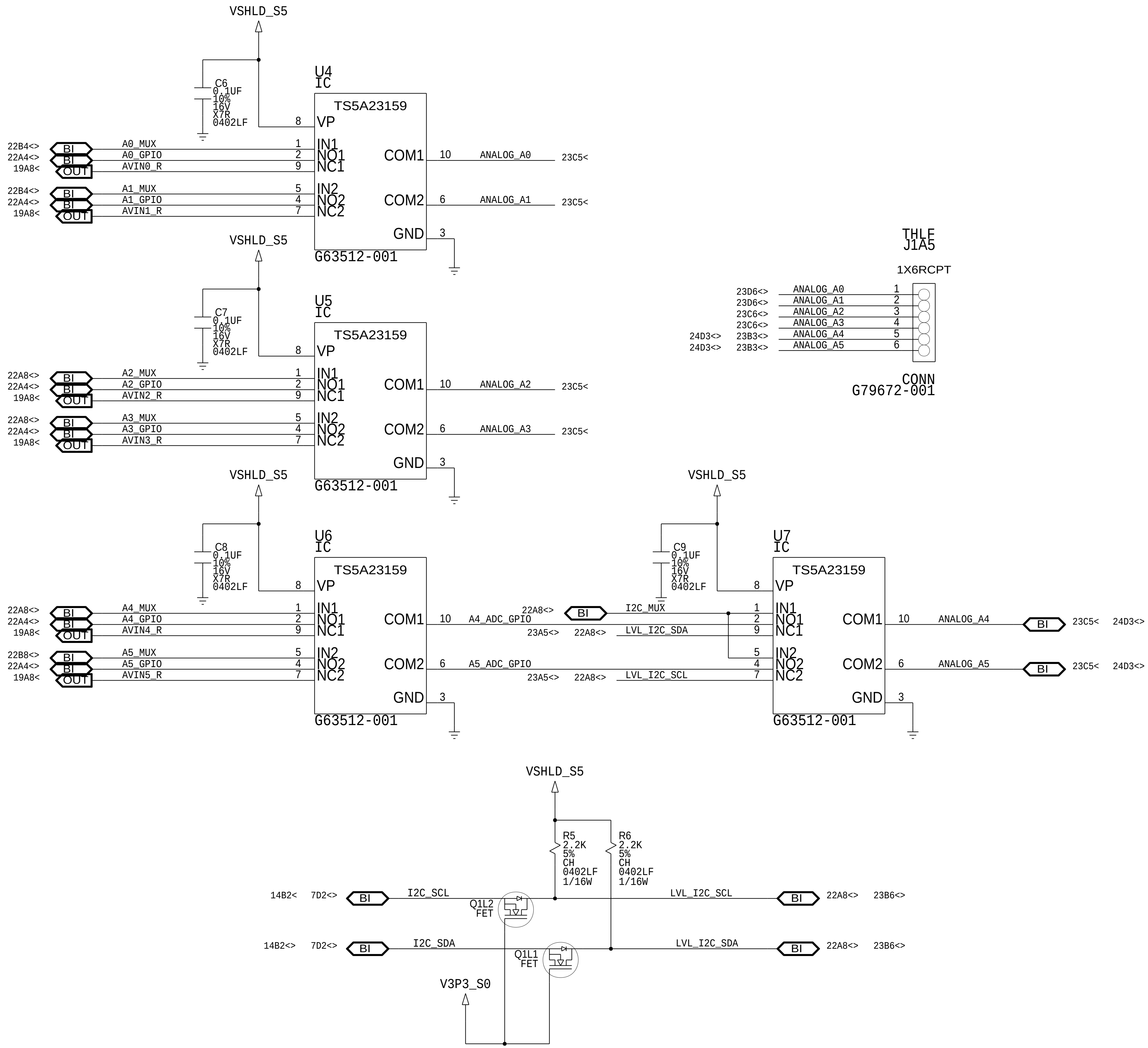
INTEL CORPORATION
2111 NE 25TH AVENUE
HILLSBORO OR 97124

TITLE: GALILEO
EXTERNAL IO MUXING

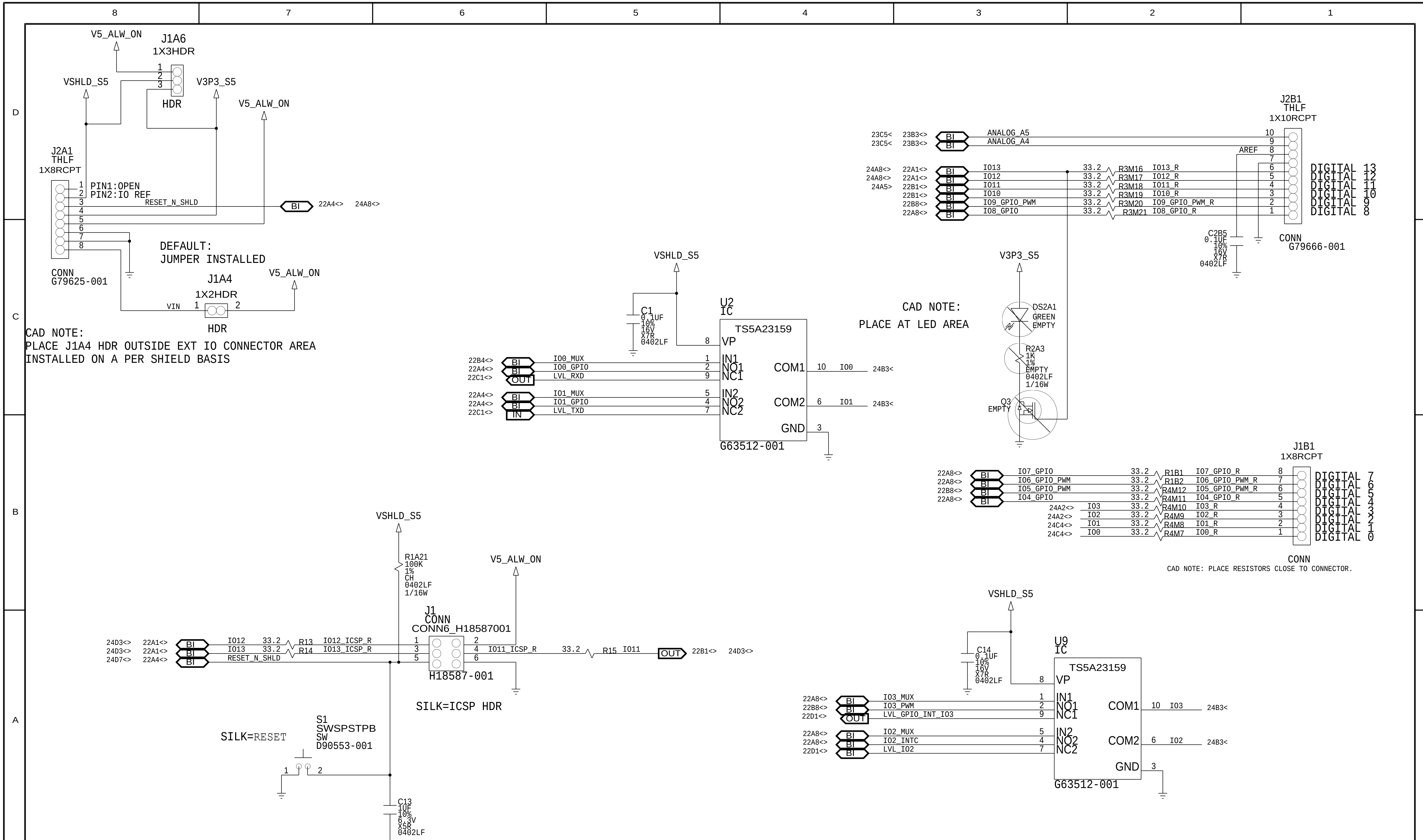
DOCUMENT NUMBER: G87171

REV: 1.0

SHEET 21 OF 27



INTEL CORPORATION 2111 NE 25TH AVENUE HILLSBORO OR 97124	DOCUMENT NUMBER: G87171
TITLE: GALILEO ANALOG CONNECTOR & MUXES	REV: 1.0 — SHEET 22 OF 27



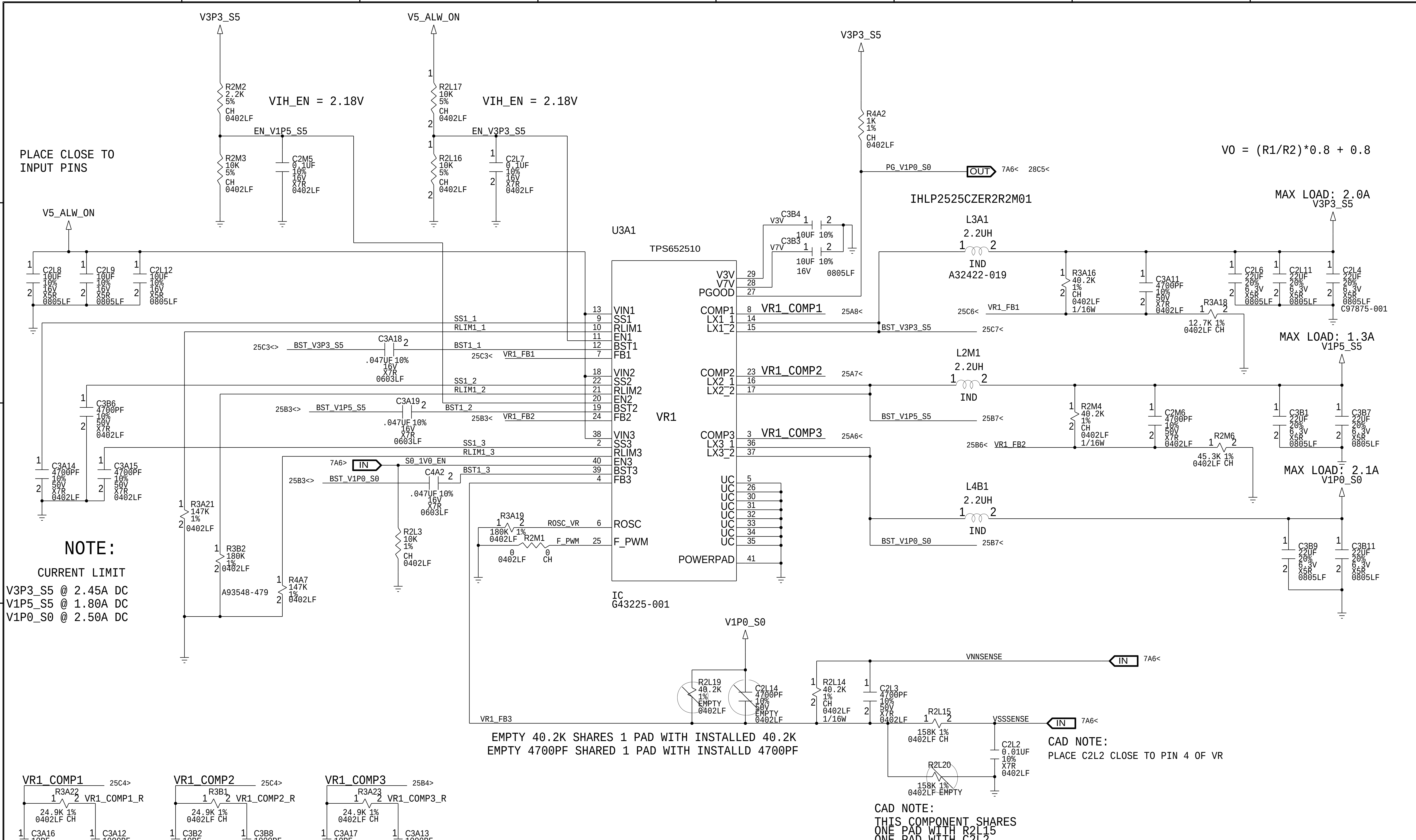
INTEL CORPORATION
2111 NE 25TH AVENUE
HILLSBORO OR 97124

DOCUMENT NUMBER: G87171

TITLE: GALILEO
EXTERNAL IO CONNECTORS

REV: 1.0

SHEET 23 OF 27

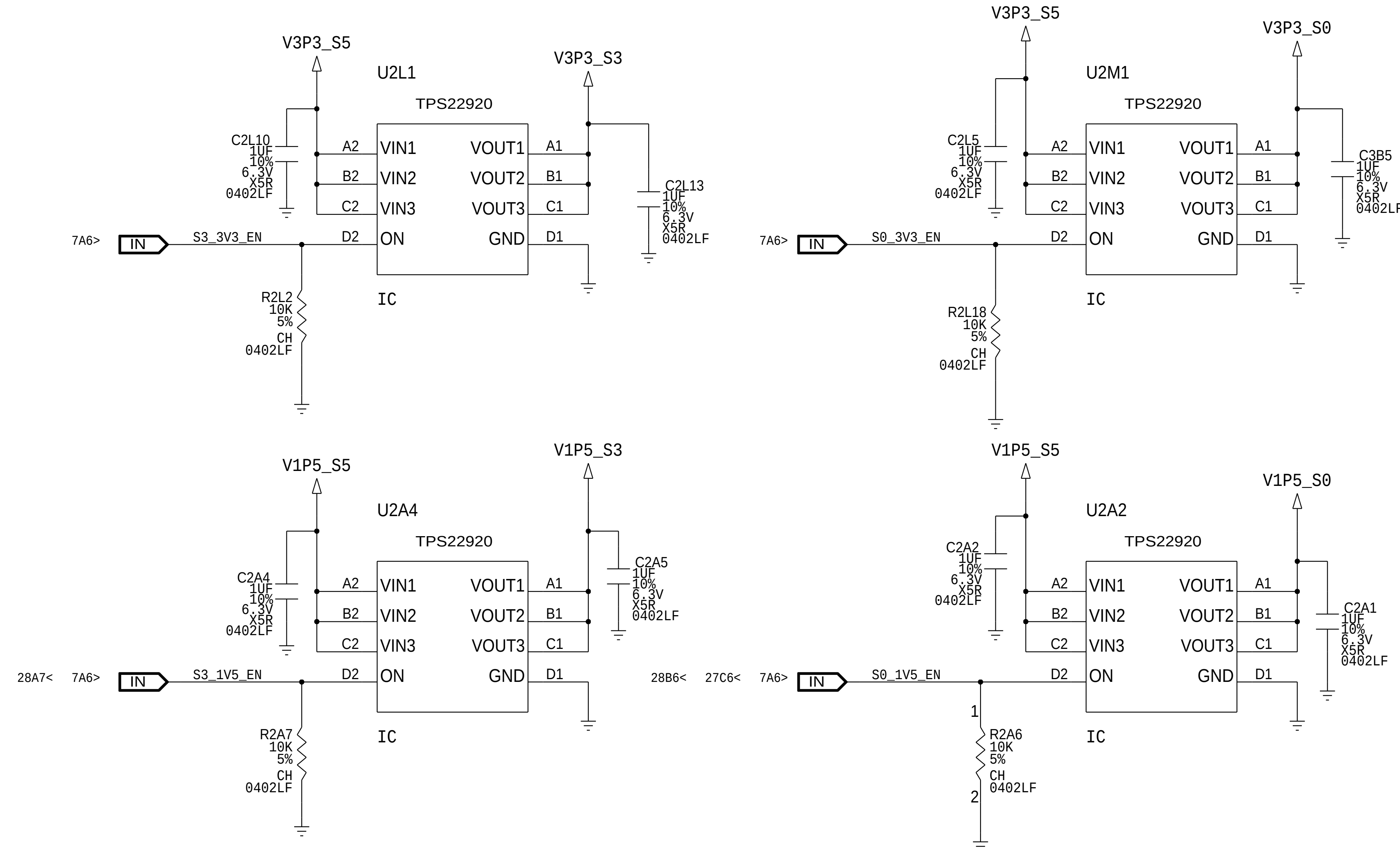


INTEL CORPORATION
2111 NE 25TH AVENUE
HILLSBORO OR 97124

DOCUMENT NUMBER: G87171	
TITLE: GALILEO VOLTAGE REGULATORS	
REV: 1.0	SHEET 24 OF 27

V3P3_S5 IS GENERATED W ON-BRD REGULATOR

V1P5_S5 IS GENERATED W ON-BRD REGULATOR

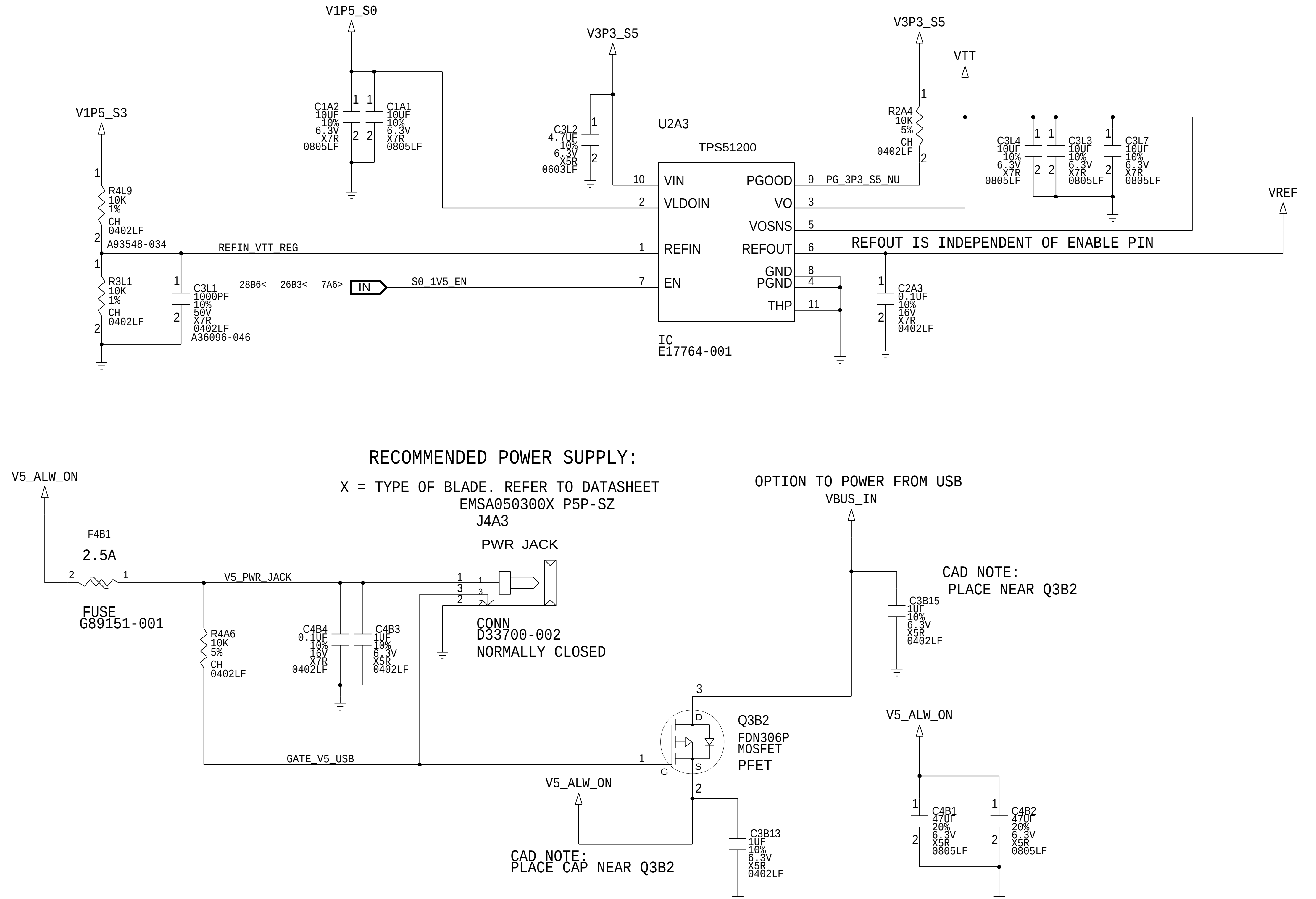


CAD NOTE:
PLACE DECOUPLING CAPS AS CLOSE AS POSSIBLE TO SWITCH PINS

V1P0_S5 IS GENERATED INTERNALLY

V1P0_S3 IS GENERATED INTERNALLY

V1P0_S0 IS GENERATED W ON-BRD REGULATOR



CONNECTOR TRUTH TABLE

PWR BRICK IN	PIN2&PIN3 DISCONNECTED	PIN3=PU TO 5V	V5_ALW_ON=BRICK PWR
PWR BRICK OUT	PIN2&PIN3 SHORTED	PIN3=GND	V5_ALW_ON=VBUS_IN

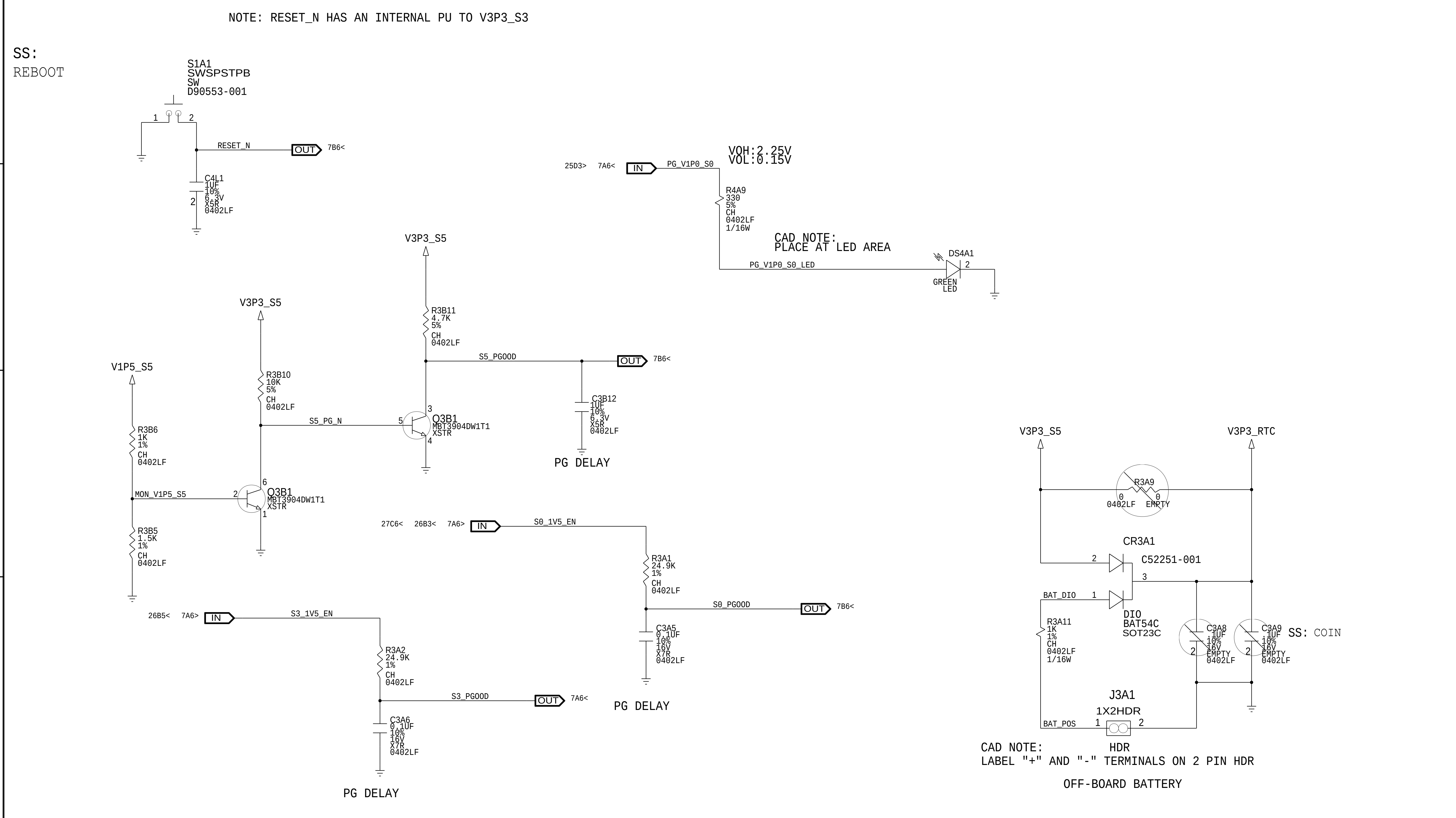
INTEL CORPORATION
2111 NE 25TH AVENUE
HILLSBORO OR 97124

TITLE: GALILEO
VOLTAGE REGULATORS

DOCUMENT NUMBER: G87171

REV: 1.0

SHEET 26 OF 27



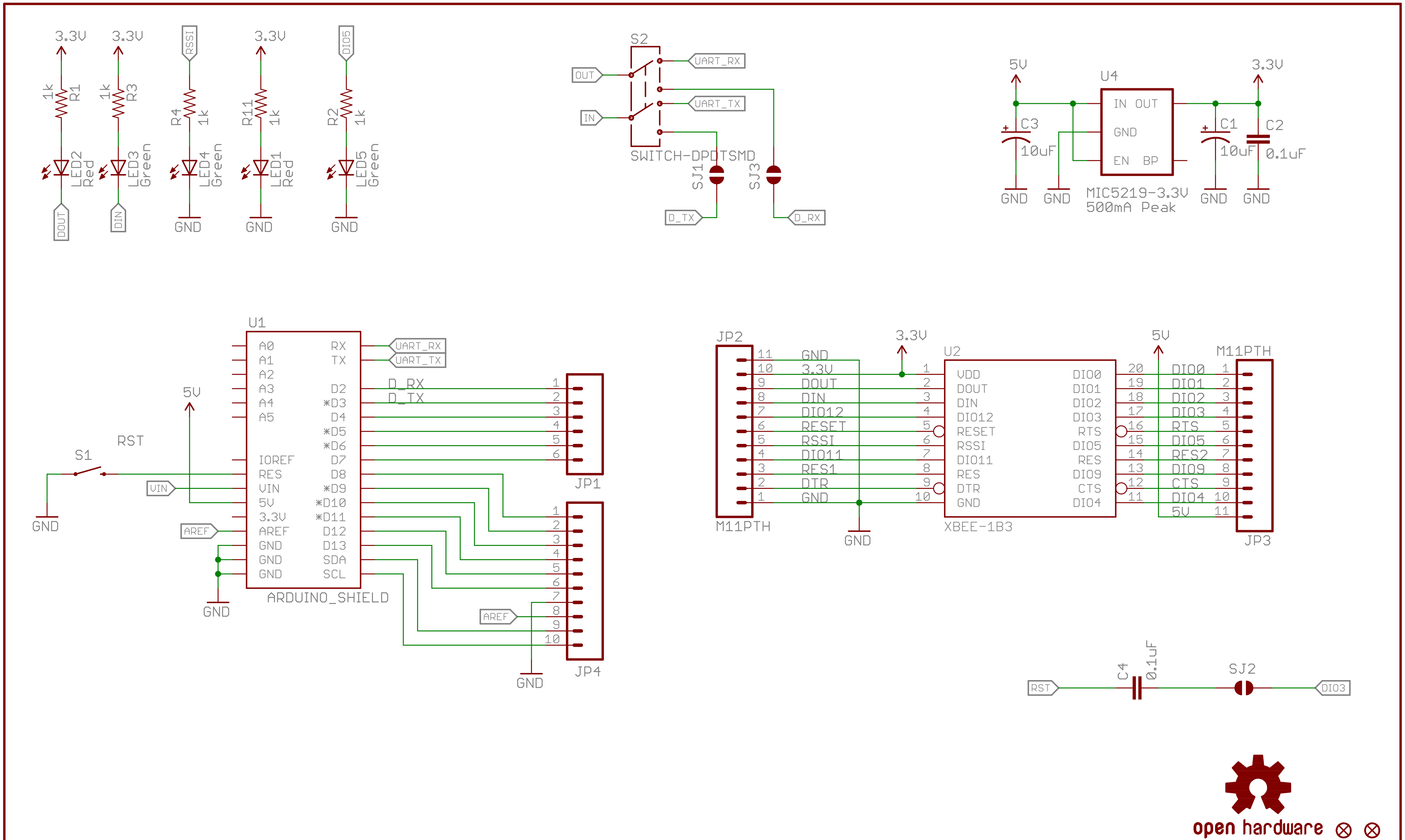
INTEL CORPORATION
2111 NE 25TH AVENUE
HILLSBORO OR 97124

TITLE: GALILEO
POWER BUTTONS & MISC

DOCUMENT NUMBER: G87171

REV: 1.0

SHEET 27 OF 27



TITLE: Xbee_shield_v15

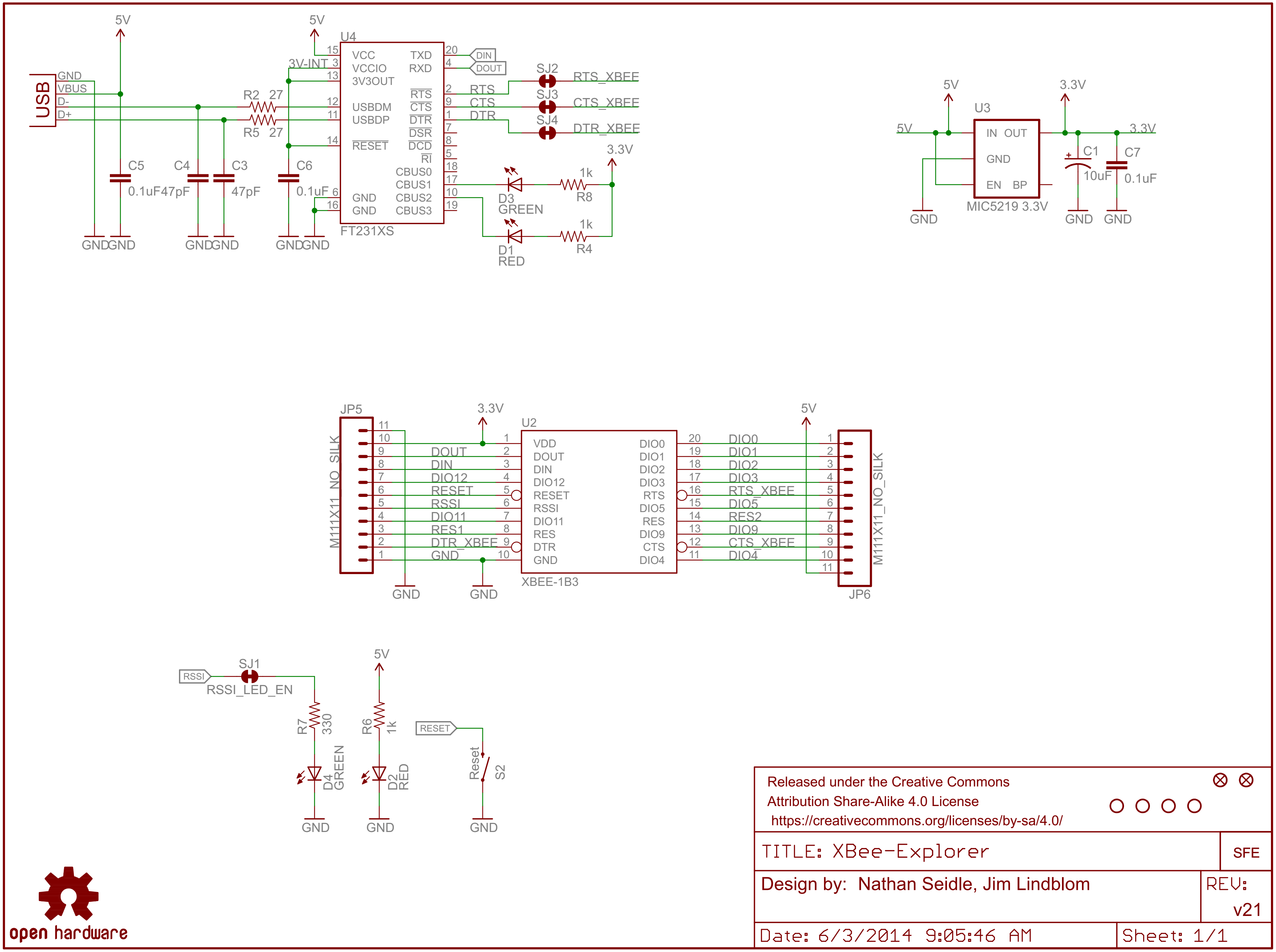
SFE

Design by: Aaron Weiss
Revised by: Patrick Alberts

REV: v15

Date: 4/5/2014 10:16:42 AM

Sheet: 1/1


USB
GND
VBUS
D-
D+
5V
C5
0.1uF
C4
47pF
C3
47pF
C6
0.1uF
R2 27
R5 27
3V-INT
U4
VCC
VCCIO
3V3OUT
USBDM
USBDP
RESET
GND
GND
TXD
RXD
RTS
CTS
DTR
DSR
DCD
RI
CBUS0
CBUS1
CBUS2
CBUS3
FT231XS
DIN
DOUT
SJ2
SJ3
SJ4
RTS_XBEE
CTS_XBEE
DTR_XBEE
3.3V
D3
GREEN
R8
1k
D1
RED
R4
1k
U3
IN OUT
GND
EN BP
MIC5219 3.3V
C1
10uF
C7
0.1uF
JP5
M111X11_NO_SILK
U2
VDD
DOUT
DIN
DIO12
RESET
RSSI
DIO11
RES
DTR
GND
DIO0
DIO1
DIO2
DIO3
RTS
DIO5
RES
DIO9
CTS
DIO4
XBEE-1B3
DIO0
DIO1
DIO2
DIO3
RTS_XBEE
DIO5
RES2
DIO9
CTS_XBEE
DIO4
RES1
DTR_XBEE
JP6
RSSI
SJ1
RSSI_LED_EN
R7
330
D4
GREEN
R6
1k
D2
RED
RESET
Reset
S2
open hardware
Released under the Creative Commons
Attribution Share-Alike 4.0 License
https://creativecommons.org/licenses/by-sa/4.0/
TITLE: XBee-Explorer
SFE
Design by: Nathan Seidle, Jim Lindblom
REV:
v21
Date: 6/3/2014 9:05:46 AM
Sheet: 1/1