Analysis and optimization of DC supply range for the ESP32 development board

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Abstract

ESP32 is becoming a popular and potential game-changer in the IoT industry. Once a code completed, to takeoff out of a USB power, questions rise about powering it. What's the feasible external voltage range? What's the current? Which cell battery? And so on. These questions cannot be easily resolved by only skimming datasheets. This paper went over to clarify the obscure information about the DC supply range for the ESP32 development board, especially ESP32-DevKitC V4. The results were disclosed through investigation, calculation, experiments, and LTspice simulation. Starting from getting relevance facts from datasheets of essential components on the board, calculated thermal conditions of heated component, experimented to confirm the calculated and get practical data while code running including GPIO and WiFi, and ended with simulation to confirm the data.

This paper concludes the following result points. The minimum supply voltage is 3.6 V to run an ESP32 module. The supply voltage should be under 10 V for both input capacitor rated voltage and LDO junction temperature rating. The thermal restriction was calculated at an ambient temperature of 25 °C and tried and tested. For a more harsh environment, the upper limit voltage could be derated in this way. An external power should be able to supply current well over average 100 mA; a good 1 A. In terms of battery, this range reassures that an ESP32 can run with a single cell LiPo. Regarding the USB, both the high power and low power port can supply sufficiently.

While an external supply being no less than 5.2 V, both the USB and external sources could work simultaneously.

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Index Terms

ESP32, Internet of things (IoT), Embedded systems, Microcontrollers, Thermal management of electronics

I. Introduction

ESPRESSIF's ESP32 microcontroller is becoming popular in the embedded and IoT industry due to its many pros [1]. Its dual-core speeds up and FreeRTOS support attracts more and more developers [2]. Also, Espressif provides the ESP32 module and AWS[1] certified development board `ESP32-DevKitC V4` at an affordable price for makers or developers to get easily started even on a breadboard. Moreover, one can write the code on the programming environment ESP-IDF (Espressif IoT Development Framework) or even with Arduino IDE, which makes diverse kinds of users could handle it from high school science club to experienced industry experts.

To power the development board, there are two options; `USB` or `EXT_5V` pin on the connector J2 as shown in Fig. 1. This paper primarily focuses on using the `EXT_5V` pin. Another way of giving 3.3 V directly to the `3.3V` pin is beyond the scope of this paper.

The `EXT_5V` pin doesn't have to be exact 5.0 V due to no 5 V user component on the board except for the LDO, U2 AMS1117-3.3 [4]. The U1 CP2102 (USB to UART bridge) gets the `USB` VBUS (5 V from `USB`).

Regarding using the `EXT_5V`, there could happen a controversy or fallacy for anyone who has little time to ponder the hardware. To get the correct decision, this paper introduces a reliable supply range to the `ESP32-DevKitC V4` or compatibles out of both intuitive and quantitative analysis.

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II. Approach

A. Components Electrical Characteristics

Table I shows the electrical characteristics of the essential components in Fig. 1 [4][5][6][7].

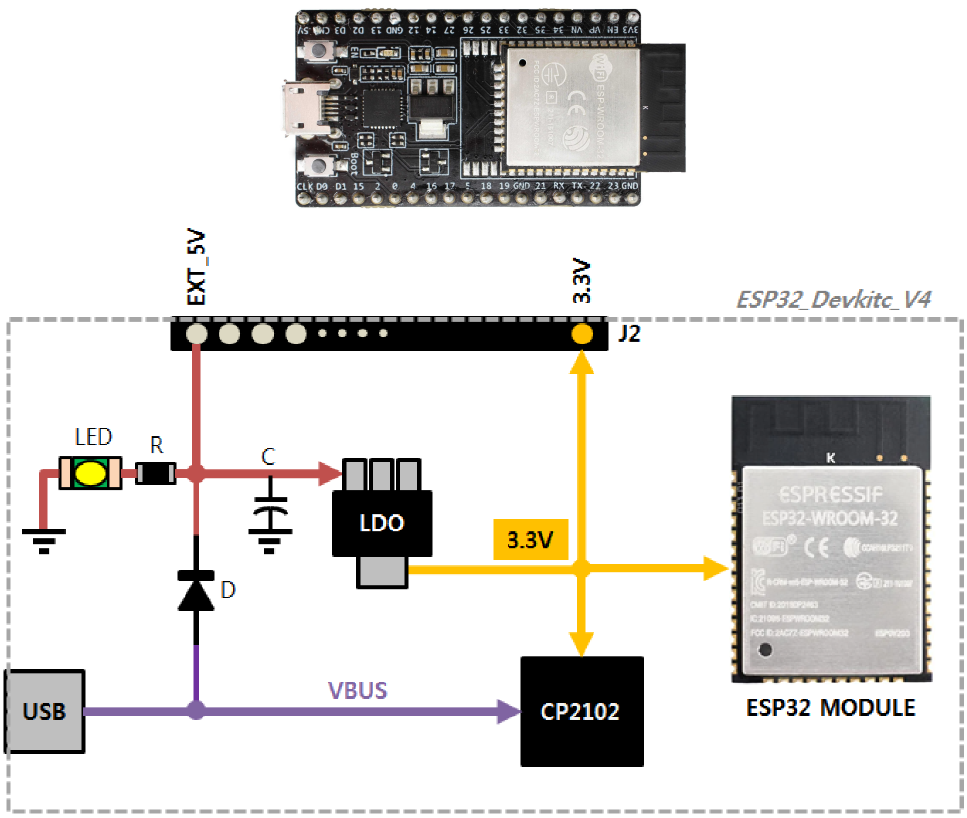

Fig. 1. ESP32 development board and its simplified power path out of `ESP32-DevKitC V4` circuit diagram

TABLE I
Essential characteristics of components on the $\mathrm{V_{EXT\_5V}}$ or $\mathrm{V_{3.3V}}$ nets

	C	LDO	CP2102	ESP32
V_{max}	10 V	15 V	3.6 V	3.6 V
V_{min}			3.0 V	2.3 V
I_{norm}			20 mA	80 mA
I_{PU}			0.2 mA	
I_{Lim}		900 mA		
P_{Dmax}		1.2 W		

$\mathrm{V_{EXT\_5V}}$, the supplied voltage to J2 `EXT_5V` pin, covers through C, 22µF/10V ceramic capacitor, and input of LDO which downward regulates to 3.3 V for the ESP32 module and CP2012. The three constraints are as follows:

1) The minimum $\mathrm{V_{EXT\_5V}}$ has to satisfy for the LDO to supply V_{min} to both CP2102 and ESP32. Let $\mathrm{V_{EXT\_5V}}$ and $\mathrm{V_{3.3V}}$ denote the input range to the LDO and corresponding output region respectively, a function f maps the two spaces; $f : \mathrm{V_{EXT\_5V}} \rightarrow \mathrm{V_{3.3V}}$

$$f(x) \geq max\{V_{min\,CP2012}, V_{min\,ESP32}\}\ ,\ x \in \mathrm{V_{EXT\_5V}} \tag{1}$$

2) $\mathrm{V_{EXT\_5V}}$ should be less than the capacitor C rated voltage, 10 V.

$$\mathrm{V_{EXT\_5V}} < 10\ \mathrm{V} \tag{2}$$

3) The LDO confines power dissipation at most 1.2 W to guarantee its line and load regulation [6]. Where P_D is the power dissipation of LDO, U2 AMS1117-3.3,

$$P_D \le 1.2 \text{ W} \tag{3}$$

B. Minimum Input Voltage

To satisfy Equation (1), $f(x)$ looks to have to be greater than $V_{min\,CP2012}$ in Table I. However, CP2012 only works while coding phase binary update or console diagnostics under USB supplied. Once USB disconnected, CP2012 consumes I_{PU} 200 µA while do actually nothing. So ESP32's V_{min} is crucial as long as supplied from EXT_5V. ESP32's datasheet shows its $V_{min} = 2.3$ V and average current $I_{norm} = 80$ mA [5]. To confirm these terms two experiments carried out.

- The first experiment outputted GPIO PWM at frequency 300 kHz and duty swept from 0 to 100% every second with no RF.
- The latter ran a web server that treats three query packets a second.

For the experiment, BK precision 9206 bench power supplied at 2 A current limit with 18 AWG 80 cm stranded wire to the development board. Fluke 8846A measured average current I_{norm} with Analyze function.

As far as the board boot and run the codes, V_{EXT_5V} was adjusted to the minimum, where $V_{3.3V}$ and I_{norm} were recorded and P_D was calculated accordingly in Table II.

TABLE II
MINIMUM VOLTAGE EXPERIMENT RESULT

Experiment	WiFi	V_{EXT_5V}	$V_{3.3V}$	I_{norm}	P_D
1. LED PWM (300 kHz)	X	3.5 V	2.5 V	42 mA	0.042 W
2. Web Server	O	3.6 V	2.6 V	100 mA	0.100 W

C. Maximum Input Voltage

Under the conditions (2) and (3), the maximum V_{EXT_5V} is bounded by LDO's junction temperature out of power dissipation determined by the following equation.

$$P_D = \frac{T_j - T_a}{\theta_{ja}} \tag{4}$$

$$\begin{aligned} P_D &= \text{power dissipation in watts} \\ T_j &= \text{maximum junction temperature} \\ T_a &= \text{operating temperature} \\ \theta_{ja} &= \text{thermal resistance from the device junction to ambient} \end{aligned}$$

The LDO AMS1117-3.3 datasheet shows that T_j is rated at 125 °C, θ_{ja} is 90 °C/W at an ambient temperature of T_a = 25 °C [6]. Little copper pad beneath the LDO on the development board retains the θ_{ja} underrated [3]. Substituting these numbers into Equation (4) gives maximum $P_D =$ which is in this case less than 1.1 watts.

$$P_D < \frac{125\,°\text{C} - 25\,°\text{C}}{90\,°\text{C/W}} = 1.1\,\text{W} \tag{5}$$

The LDO's power dissipation has to be less than 1.1 W, which is included in the constraint (3). Applying the current 100 mA from Table II, the maximum V_{EXT_5V} could be calculated. However, the result exceeds the capacitor rated voltage (2), which remains dominant.

To validate the condition (2) meets the thermal limitation (5), the same codes in section II-B ran with $\mathrm{V_{EXT\_5V}} = 9\ \mathrm{V}$. Additionally measured was case temperature T_c converging over running 6 hours in a 25 °C air-conditioned room. Omega UWBT thermometer captured the T_c with a thermocouple on the LDO tab.

TABLE III
$\mathrm{V_{EXT\_5V}}$ = 9 V EXPERIMENT RESULT

Experiment	WiFi	T_c	$\mathrm{V_{3.3V}}$	I_{norm}	P_D
1. LED PWM (300 kHz)	X	40 °C	3.3 V	46 mA	0.26 W
2. Web Server	O	54 °C	3.3 V	100 mA	0.57 W

III. RESULTS

From Table II and III, the Equations (1) and (2) result simplified to

$$2.6\,\mathrm{V}\ \leq\ f(x \in \mathrm{V_{EXT\_5V}})\ \leq\ 3.3\,\mathrm{V}\ ,\ \mathrm{V_{EXT\_5V}} := \{x \in \mathbb{R}\,|\,3.6 \leq x < 10\}\ \mathrm{V} \tag{6}$$

At least $\mathrm{V_{EXT\_5V}}$ 3.6 V assures the minimum $\mathrm{V_{3.3V}}$ 2.6 V for RF applications can work in order.

Table III shows that the condition (2) complies with the LDO's thermal restriction. From the measured T_c and T_a, the junction temperature can be estimated far below the rated T_j. We conclude the available $\mathrm{V_{EXT\_5V}}$ range.

$$\therefore\ 3.6\,\mathrm{V}\ \leq\ \mathrm{V_{EXT\_5V}}\ <\ 10\,\mathrm{V} \tag{7}$$

IV. DISCUSSION

A. Simulation

An LTspice circuit simulation reassured the result condition (7). Advanced Monolithic Systems, the AMS1117 manufacturer, doesn't provide its SPICE model. So a very similar LT1117-3.3 library acted the LDO [9]. The input voltage swept from 3 V to 9 V linearly in the simulation circuit Fig. 2. As a load, a current source sunk 50 mA, 100 mA, and 200 mA respectively.

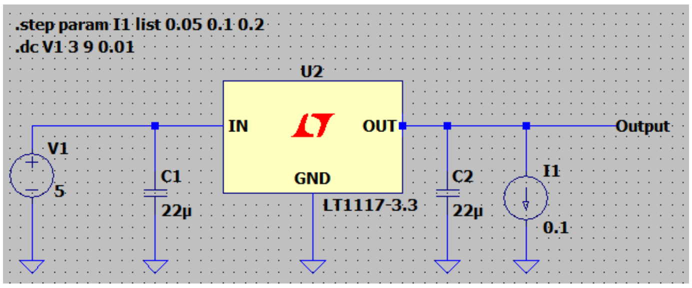

Fig. 2. Simulation circuit for LDO response to varying input. Capacitor C1 and C2 have the same value as in the `ESP32-DevKitC V4` circuit.

The simulation outcome in Fig. 3 shows that the input 3.6 V makes output 2.6 V, which is exactly the experiment result in Table II. The LDO response is consistent regardless of the load current variance.

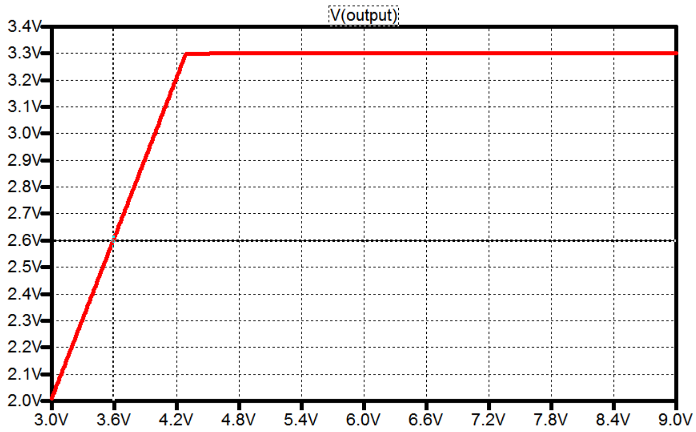

Fig. 3. Simulation result. The horizontal axis ≡ input voltage, vertical axis ≡ output voltage. LDO makes 2.6 V at input 3.6 V.

B. USB

USB is prevalent to be used with no problem. The `USB` VBUS ranges from 4.4 V ∼ 5.5 V at Low-power Port, and 4.7 V ∼ 5.5 V at High-power Port [8]. Where V_f is the diode D BAT760-7 forward voltage drop max 0.5 V [10], the worst-case LDO input is

$$\begin{aligned} \mathrm{VBUS}_{min} - V_{f(max)} &= 4.4\,\mathrm{V} - 0.5\,\mathrm{V} &= 3.9\,\mathrm{V} \quad &\text{(Low-power Port)} \\ \mathrm{VBUS}_{min} - V_{f(max)} &= 4.7\,\mathrm{V} - 0.5\,\mathrm{V} &= 4.2\,\mathrm{V} \quad &\text{(High-power Port)} \end{aligned}$$

Either the USB Low-power port or High-power port sufficiently meets Equation (7), for the LDO to supply ESP32 sufficiently.

C. Battery-powered system

A single-cell LiPo battery that covers 3.7 V ∼ 4.2 V confirms the requirement (7). It can directly supply the ESP32 development board.

D. Dual power source at the same time

Could the `USB` power and `EXT_5V` be used simultaneously? In Fig. 1, a diode D BAT760-7 exists between the VBUS and `EXT_5V` [4]. It has forward voltage drop $V_f = 0.3\,\mathrm{V} \sim 0.5\,\mathrm{V}$ [10]. Now that the diode protects current flows from the `EXT_5V` to the VBUS net, $\mathrm{V}_{\mathrm{EXT\_5V}}$ no less than 5.2 V causes no problem while the `USB` lives at the same time.

$$\begin{aligned} \mathrm{VBUS}_{max} - V_{f(min)} \le \mathrm{V}_{\mathrm{EXT\_5V}} &< 10\,\mathrm{V} \\ 5.2\,\mathrm{V} \le \mathrm{V}_{\mathrm{EXT\_5V}} &< 10\,\mathrm{V} \end{aligned} \tag{8}$$

V. Conclusions

It would better to employ the V_{min} value a bit higher than the ESP32 datasheet's. It should be at least 2.6V to run an ESP32 module from an experiment, especially for the RF application. An ESP32 module consumes currents average around 100 mA while RF works busily.

An external supply voltage $\mathrm{V}_{\mathrm{EXT\_5V}}$ should be in at least 3.6 V and under 10 V. The lower limit is for the ESP32's V_{min}. The higher bound concerns both the input capacitor rated voltage and LDO's rated junction temperature. The thermal condition was calculated and tested at an ambient temperature of 25 °C. However, one could refine and derate the upper limit voltage in this way for more harsh environments.

Both the `USB` and `EXT_5V` could work simultaneously while the V_{EXT_5V} condition (8) meets.

The `ESP32-DevKitC V4` is flawless for either a single cell battery-powered or USB powered.

VI. Acknowledgments

I would like to thank Liu Jia, John Lee, and Yanchen Lu at Espressif Systems for their support and advice to this work.

Glossary

CP2102 includes a USB 2.0 full-speed function controller, USB transceiver, oscillator and Universal Asynchronous Receiver/Transmitter (UART) and eliminates the need for other external USB components required for development. All customization and configuration options can be selected using a simple GUI-based configurator. 1, 2

ESP32 is a series of low-cost, low-power system on a chip microcontrollers with integrated Wi-Fi and dual-mode Bluetooth. The ESP32 series employs a Tensilica Xtensa LX6 microprocessor in both dual-core and single-core variations and includes built-in antenna switches, RF balun, power amplifier, low-noise receive amplifier, filters, and power-management modules. ESP32 is created and developed by Espressif Systems, a Shanghai-based Chinese company, and is manufactured by TSMC using their 40 nm process. It is a successor to the ESP8266 microcontroller. 1–3

ESP32-DevKitC V4 is an AWS-qualified development board. In addition to Espressif's own ESP-IDF SDK, you can use FreeRTOS on ESP32-DevKitC. FreeRTOS provides out-of-the-box connectivity with AWS IoT, AWS Greengrass and other AWS services. It contains the entire basic-support circuitry for ESP32-WROOM-32D, ESP32-WROOM-32U, ESP32-WROVER-B and ESP32-SOLO-1, including a USB-UART bridge, reset- and boot-mode buttons, an LDO regulator and a micro-USB connector. Every important GPIO is available to the developer. 1

Espressif Systems is a public multinational, fabless semiconductor company, headquartered in Shanghai and offices China, India and Czechia. Founded in 2008, Espressif Systems main product is the ESP32 microcontroller. 1

Acronyms

DC Direct Current. 3

LDO Low-Dropout Regulator. 1, 2

LiPo Li-Ion/Po, Lithium-Ion Polymer. 3

UART Universal Asynchronous Receiver Transmitter. 2

USB Universal Serial Bus. 2

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