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 take off without 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 quickly 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 investigation, calculation, experiments, and LTspice simulation disclosed the result. Starting from getting relevance facts from datasheets of essential components on the board, calculated thermal conditions of the heated element, experimented to confirm the deliberate and get empirical data while code running including GPIO and WiFi, and ended with simulation ensure 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, this way could derate the upper limit voltage. An external power should 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.

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 quickly start even on a breadboard. Moreover, one can write the code on the programming environment ESP-IDF (Espressif IoT Development Framework) or Arduino IDE, making diverse users handle it from high school science clubs to experienced industry experts.

There are two options to power the development board: `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 precise 5.0 V due to no 5 V user component on the board except for the LDO, U2

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[1]Amazon Web Services

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. This paper introduces a reliable supply range to the `ESP32-DevKitC V4` or compatibles out of both intuitive and quantitative analysis to efficiently resolve the obscureness.

II. APPROACH

A. Components Electrical Characteristics

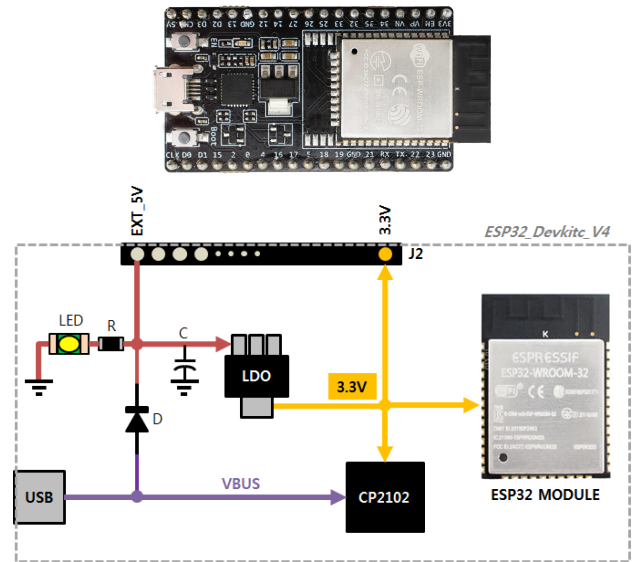Table I shows the electrical characteristics of the essential components in Fig. 1 [4][5][6][7].

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 V_{EXT_5V} OR $V_{3.3V}$ 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		

V_{EXT_5V}, the supplied voltage to J2 `EXT_5V` pin, covers capacitor C, 22 µF/10V ceramic, and LDO input, which

downward regulates to 3.3 V ESP32 module and CP2102. The three constraints are as follows:

1) The minimum V_{EXT_5V} has to satisfy for the LDO to supply V_{min} to both CP2102 and ESP32. Let V_{EXT_5V} and $V_{3.3V}$ denote the input range to the LDO and corresponding output region respectively, and a function f maps the two spaces; $f : V_{EXT\_5V} \rightarrow V_{3.3V}$

$$f(x) \geq max\{V_{min\,CP2102}, V_{min\,ESP32}\}\,,$$
$$x \in V_{EXT\_5V} \qquad (1)$$

2) V_{EXT_5V} should be less than the capacitor C rated voltage, 10 V.

$$V_{EXT\_5V} \; < \; 10 \text{ V} \qquad (2)$$

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,

$$P_D \leq 1.2 \text{ W} \qquad (3)$$

B. Minimum Input Voltage

To satisfy (1), $f(x)$ looks to have to be greater than $V_{min\,CP2102}$ in Table I. However, CP2102 only works while coding phase binary update or console diagnostics under USB supplied. Once the USB is disconnected, CP2102 consumes I_{PU} 200 μA while doing 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 the average current $I_{norm} = 80$ mA [5]. Two experiments ran to confirm these terms.

- 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} decreased to the minimum, where Table II recorded $V_{3.3V}$ and I_{norm} and calculated P_D accordingly.

TABLE II
MINIMUM VOLTAGE EXPERIMENT RESULT

Experiment	WiFi	V_{EXT_5V}	$V_{3.3V}$	I_{norm}	P_D
1. LED PWM	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 (4).

$$P_D = \frac{T_j - T_a}{\theta_{ja}} \qquad (4)$$

P_D = power dissipation in watts
T_j = maximum junction temperature
T_a = operating temperature
θ_{ja} = thermal resistance from the device junction to ambient

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

$$P_D \; < \; \frac{125\,°C - 25\,°C}{90\,°C/W} = 1.1\,W \qquad (5)$$

The LDO's power dissipation has to be less than 1.1 W, which also satisfies the constraint (3). The P_D and current 100 mA out of Table II could calculate the maximum V_{EXT_5V}. 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 $V_{EXT\_5V} = 9$ 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
V_{EXT_5V} = 9 V EXPERIMENT RESULT

Experiment	WiFi	T_c	$V_{3.3V}$	I_{norm}	P_D
1. LED PWM	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

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

At least V_{EXT_5V} 3.6 V assures the minimum $V_{3.3V}$ 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 V_{EXT_5V} range.

$$\therefore \; 3.6\,V \; \leq \; V_{EXT\_5V} \; < \; 10\,V \qquad (7)$$

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.
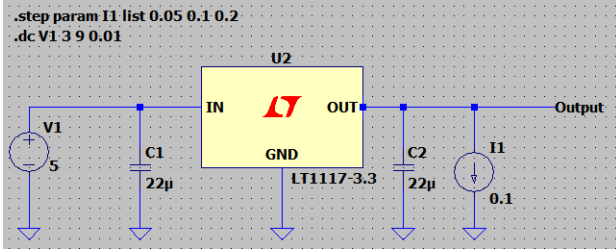

Fig. 2. Simulation circuit for LDO response to varying input. Capacitor C1 and C2 have the same value as in the `ESP32-DevKitC V4` circuit.
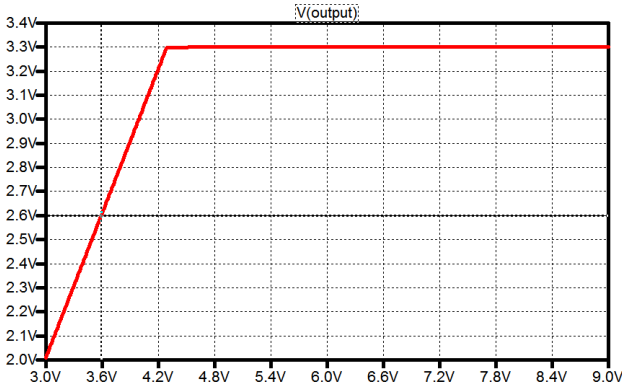

Fig. 3. Simulation result. The horizontal axis ≡ input voltage, vertical axis ≡ output voltage. LDO makes 2.6 V at input 3.6 V.

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

B. USB

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

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

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

C. Battery-powered system

A single-cell LiPo battery that covers 3.7 V $\sim$ 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 $V_f = 0.3\,\text{V} \sim 0.5\,\text{V}$ [10]. Now that the diode protects current flows from the `EXT_5V` to the VBUS net, $V_{\text{EXT\_5V}}$ no less than 5.2 V causes no problem while the `USB` lives simultaneously.

$$\text{VBUS}_{max} - V_{f(min)} \leq V_{\text{EXT\_5V}} < 10\,\text{V}$$
$$5.2\,\text{V} \leq V_{\text{EXT\_5V}} < 10\,\text{V} \quad (8)$$

V. Conclusions

This paper deciphers pertinent datasheets and papers to disclose and clarify primary facts for designing the power supply chain for the ESP32 module and reassured them with experiment and simulation.

It would be better to go for the V_{min} value a bit higher than that of the ESP32 datasheet, which must be in an ideal laboratory environment; At least 2.6 V is recommended to run an EPS32 module an RF application from an experiment.

This paper suggests considering the average current consuming 100 mA while RF works busily.

At least 3.6 V and under 10 V, the available external supply voltage $V_{\text{EXT\_5V}}$ range introduces. The lower limit is for the ESP32's V_{min}. The upper bound concerns both the input capacitor rated voltage, and LDO's rated junction temperature. Even though the thermal condition was calculated and tested at an ambient temperature of 25 °C, 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 $V_{\text{EXT\_5V}}$ condition (8) meets.

The `ESP32-DevKitC V4` can be said flawless for powered by either a single cell battery or USB.

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